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FEMALE UPPER BODY DYNAMIC STRENGTH REQUIREMENTS IN HIGH PERFORMANCE AIRCRAFT: A SELECTED BIBLIOGRAPHY

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13. ABSTRACT (Maximum 200 words)

The Presidential Commission on the Assignment of Women in the Armed Forces has expanded the role of women in the military with its new "gender-neutral" assignment policy. NAWCADWAR is conducting a series of tests to determine "gender neutral" dynamic strength requirements for small stature females performing operationally relevant tasks in a high performance cockpit. This report contains a bibliography of the results of a literature review conducted prior to drafting a human use test plan. It is not intended to be an extensive review of all areas in which male and female strength capabilities differ. Instead it highlights information pertinent to strength assessments in general, measurement modalities and interpretation, published male and female strength data as well as extrapolated female strength capabilities under normal and in acceleration environments and specific strength requirements associated with high performance flight under normal and emergency conditions. It also contains a list of other bibliographies which compile gender related differences in human factors and performance.

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I.   ISOMETRIC MUSCULAR STRENGTH AND DYNAMIC MUSCULAR EXERTION

1. Chaffin DB, Andersson GBJ. Occupational biomechanics, 2nd ed. New York:John Wiley & Sons, Inc., 1991.

The following is a summary of Chapter 4 "Muscle Strength."

Strength varies between people and tasks, static (isometric) strengths are not necessarily correlated with dynamic exertions and several different measurement criteria must be met to develop and use strength data successfully. Maximum voluntary exertion levels are probably below the physiological tolerance of the muscle-tendon-bone system, thereby providing a "safety factor."

Skeletal muscles operate to produce body segment rotations and measures can either be (1) a force produced at some point on the body or (2) a moment (torque) produced about a given joint. For specific localized body action (e.g. manipulating a control), the latter are often used. The latter are also important in modelling human strength, as they depict muscle moment capabilities at various joints.

Static exertions can be maintained for 4 - 6 s, during which the instantaneous peak and a mean value (first 3 s) can be recorded. If the same muscle groups are retested, a minimum 2 min rest period is recommended. Instructions given to a subject can greatly affect static strength performance. For example, different strength values will be obtained if subjects are told to "increase and hold their exertion to a maximum" as compared to "jerk the handle." Note that the effect is small for small muscle motions (i.e. grip strength). Also note that since the faster a muscle shortens the less tension it produces, the velocity of motion on dynamic strength tests will greatly influence the resulting strength values.

Chaffin describes the following static strength test procedures to insure repeatability and validity:
1. Exertion duration of 4 to 6 s
2. Employ a measuring device which can
         a. record peak and 3 s time averages exertion levels
         b. be applied without discomfort due to localized pressure
         c. be flexible for measuring different types of exertions
3. Allow adequate rest between exertions - 30 s to 2 min
4. Use carefully stated and consistent instructions
         a. avoid coercion, include informed consent of hazard/risks, allow a subject to have additional
              rest as requested
5. Provide positive, general verbal feedback - avoid competition between subjects
6. Minimize environmental distractions, e.g., temperature, light, spectators
7. Standardize test postures and body supports and restraints
8. Include complete reporting of test conditions, subject descriptions and statistics in reports

Dynamic strength measurements:

Body motions have two effects on muscular force capability: (1) the motion of body segments may require significant muscle force to simply accelerate the body mass and overcome inertia. There will also be a deceleration phase of any motion, resulting in momentum which will assist a muscle in producing additional effective force output. Peak strength values are highly variable due to the dynamics of the task. (2) physiology of muscle (force-velocity property) - as muscle is rapidly shortened, the maximum force will be reduced as a function of the velocity of muscle shortening. Chaffin reported that rapid arm motions (60% of arm length per s) resulted in dynamic peak strengths 75-80% of static strengths.

A major variable affecting strength, based on biomechanical and physiological factors, is posture. The muscle force required to produce a constant moment at a joint will vary inversely as the moment arm. Often a strength curve (angle vs moment curve, i.e., strength as function of joint angle) is calculated.

A Psychophysical Strength Method is often used during dynamic exertion assessments. A simulation of a task of interest is devised in which subjects are allowed to adjust the load after each attempt - continuing to make adjustments until they believe the load to be their maximum. The amount of load added/subtracted is not known to the subject until after the session is over. The initial load is also unknown to the subject, so s/he is choosing an abstract load. A modification of this technique called the "Liftest" (Kroemer, 1982) can be used in which standard weights are added one at a time to measure lifting strength. Either method requires extensive cooperation and motivation on the part of the subjects.

Arm strengths are lower when the elbow is extended and the exertion direction is perpendicular to the axis of the forearm. If the arm is flexed or abducted above the shoulder, strength values are also reduced. Seat back angle is also important as it effects arm postures and thereby exertion levels.

The frequency of lifting also effects muscular exertion capacity. As frequency increases from 1/min to 12/min, lifting limits decline linearly.

In general, female average strengths compare favorably with males for lower extremity static efforts and various dynamic lifting, pushing and pulling activities. Muscular exertions involving flexion, abduction and rotation of the arm about the shoulder appear to be particularly difficult for women as compared to men, possibly due to smaller muscle moment arms. It is important to note that gender differences reported in population strength data are almost entirely explained by differences in muscle size as estimated by lean (fat-free) body weight or limb cross-sectional area (circumference measurements) dimensions ($r \sim 0.8$). If a man and woman with similar fat-free body weight are trained to the same degree, their muscle strength performances will probably be equal.

Gross anthropometric descriptors alone are not well correlated enough with strength to be of practical value. Measuring the mobility or strength at one joint only as a predictor of general capability to reach, lift or move objects is not valid. Multiple measures are required, although a single best set of measures is unknown (or may not exist).

Electromyography (EMG): Chaffin recommends the following to ensure quality EMG recordings. Prepare the interface such that ratio of skin to amplifier input impedance is 1:10. Use a 1 MΩ input impedance amplifier with an 80 dB noise rejection ratio. It is best to have a preamplifier on the subject. An EMG waveform has a bandwidth of 10 - 1000 Hz and an input signal range from 3 μV to 2 mV. A person and activity specific "calibration curve" can be calculated by having the subject perform a measured graded exertion of the muscle or muscle group being monitored. It 's important that calibration motions and posture simulate actual conditions. Note that subtle changes in postures or motion can involve different muscle groups and that force is dependent on muscle length and velocity. These will alter relationship between desired measures and the calibration curve. This will not be a linear relationship. Changes in the EMG waveform can be used to indicate muscular fatigue. With increasing fatigue, EMG amplitude increases and frequency content decreases.

Chaffin provides citations for two mathematical strength prediction models. A two dimensional static strength prediction program can be found in Chaffin DB "A computerized biomechanical model: development and use in studying gross body actions." J. Biomech, 2: 429-41, 1969. A three dimensional version can be found in Garg A, Chaffin DB "A biomechanic computerized simulation of human strength" AIIE Trans., March, 1-15, 1975.

When studying the types of arm motions required to operate a control stick in an aircraft cockpit, the following quotations (p 397) are of value. "When attempting to perform a maximal push or pull exertion with one hand while sitting, the resulting strength performance is very dependent upon shoulder and elbow angles." (The authors recommend the use of the 3D model for strength predictions.) "In general, exertions in a lateral direction (to the left or right) with the hand close to the body requires a humeral rotation at the shoulder, and result in much lower values than exertions in the sagittal plane (in and out).

These latter type of exertions use arm flexion and extension, involving the stronger biceps, brachialis and triceps muscles."

2. Kroemer KHE, Kroemer HJ, Kroemer-Elbert KE. Engineering physiology. Bases of human factors/ergonomics. 2nd ed, New York:Van Nostrand Reinhold, 1990.

It is not unusual to find in the strength literature that the various types of exertions are improperly defined. The authors offer the following definitions:

Independent variables: items purposely manipulated to assess changes in dependent variables.
Isometric exertion: zero displacement (muscle length change).
Isokinetic exertion: velocity (rate muscle length changes) is constant while acceleration and jerk = 0.
       Mass properties are usually controlled, with force and/or repetition as the dependent
       variables. Displacement could also serve as a dependent or independent variable.
Isoforce exertion: sets the amount of force (or torque) to a constant value, usually mass properties and
       displacement are controlled independent variables and repetition is a dependent variable. When
       tension is constant, this exertion is Isotonic. Isoforce exertions are usually combined with an
       isometric condition, such as holding a load motionless.
Isoinertial exertion: mass properties are controlled.
Free dynamic exertion: nothing is controlled.
Static strength is defined as "the capacity to produce torque or force by a maximal voluntary isometric muscular exertion." Strength has vector qualities and is described by a magnitude and direction.

The authors summarize the "Caldwell Regimen" for isometric strength testing and recommend its universal adoption in isometric strength studies (* marks those which also apply to dynamic exertions).

1. Static strength is measured according to the following:
    a. Static strength is assessed during a steady exertion sustained for 4 s.
    b. Transient period of about 1 s each, before and after 1a. are disregarded.
    c. Strength datum is the mean score during the first 3 s.
2.   a*. Subject is informed about the test purpose and its procedures.
    b*. Instructions should be factual without emotional appeals.
    c. Subject instructed to "increase to maximal exertion (without jerk) in about 1 s and maintain
       this effort during a 4 s count."
    d*. Inform the subject during test about their general performance in qualitative,
       non-comparative, positive terms. Do not give instantaneous feedback during exertions.
    e*. Avoid factors affecting motivation.
3*. Minimal rest period between related efforts should be 2 min.
4*. In the report, describe conditions existing during strength testing, including
    a. body parts and muscles chiefly used,
    b. body position,
    c*. body support/reaction force available,
    d*. coupling of subject to the measuring device (to describe the location of strength vector),
    e*. strength measuring and recording device.
5. Subject description, including
    a*. population and sample selection
    b*. current health and status (medical exam and questionnaire are recommended)
    c*. gender
    d*. age
    e*. anthropometry (minimum requirement: height and weight)
    f*. type and amount of training related to strength testing
6. Data reporting includes

a*. mean (median, mode), standard deviation, skewness, minimum and maximum values, sample size.

3. Kroemer KEH. "Human strength: terminology, measurement and interpretation of data." Human Factors, 1970; 12:297-313.

This article attempts to clarify some of the ambiguities found in the strength literature. Kroemer defines strength as the "maximal force muscles can exert isometrically in a single voluntary effort." The dimensions of strength are force (or torque) over a given time. Isometric refers only to internal muscle effort and is not a description of the external effect or load. Isometric refers to an effort in which the length of the muscle remains constant during tension. The term "effort" applies to both static and dynamic muscle activities. Only during a dynamic effort does motion accompany muscle tension which results in performing mechanical work. As such the term "dynamic strength" or "static work" have little meaning. A "concentric" dynamic effort indicates that the muscle shortens actively against a resistance. An "eccentric" dynamic effort indicates that the muscle is passively lengthened by an external force. Isotonic (constant tension, variable muscle length) effort is normally found combined with an isometric force exertion. Muscles are not strained isotonically when moving a body segment against a constant resistance; during the motion the tension changes thereby changing the mechanical advantages. Readers should check that when "isotonic" is used, "dynamic" may be the more appropriate term. It is also relevant to note that when force is gradually increased until a maximum is reached, higher strength scores will be obtained.

Since strength assessments often require subjects to exert maximal forces while during operational settings, a maximal effort is rarely required, strength data may not be "fully relevant" when applied to a particular scenario. Kroemer states that "As soon as it has been established that the operator's force capacity meets or exceeds the force requirement, strength ceases to be a relevant criterion."

Kroemer lists five methods by which investigators assess fatigue. Muscular fatigue is often accompanied by changes in the thresholds in which an individual can perceive optical, acoustical and tactile stimuli. These changes may be effected by the type of work performed and the time elapsed between stopping the activity and performing the perception test is too long for strength studies. Energy consumption can be calculated by monitoring oxygen intake and/or the concentration of CO_2 produced. These measures are not sufficiently sensitive to monitor the effects of static effort responses. Physical stress, whether associated with static or dynamic efforts, will result in changes in the cardiovascular system. For example heart rate is a very sensitive indicator. Kroemer states that a combination of heart rate and energy consumption appears to be a reliable method as long as the physical stress is not "too small." However, it can be difficult to separate the effects of psychological from physiological stress. The author cites many examples of the use of a subjectively perceived strain scale. Some investigators have stated that circulatory system stress is closely related to subjectively perceived workload. One possible approach to assess the amount of physical strain and fatigue experienced is a combination of heart rate and subjectively perceived stress (note that Kroemer does not mention the use of electromyography).

Note that during a maximal isometric effort, blood flow is impeded while in dynamic work it may be facilitated. Physiological factors of oxygen supply and waste product removal rather than brute strength determine how long a dynamic effort can be maintained.

4. Kroemer KHE. "Designing for muscular strength of various populations." Wright Patterson AFB Tech report AMRL-TR-72-46, Dec 1974. (DTIC #AD-A011 537)

The author summarizes a variety of different parameters that can affect strength assessments. These are:
a. Strength varies with sex, age, profession, health and training, motivation, technique and experience, body position, cultural status and nationality.

b. Different strength scores, even on the same subject, are often not highly correlated.

c. The truly maximal force is of concern only if overstressing the control system must be considered; otherwise, the "regular" strength will apply if "regular" operational conditions apply.

d. Static strength scores are numerically larger than the weights (mass forces) recommended for dynamic lifting or carrying. The standard assumption is that a soldier can carry a load no more than 1/3 his body weight.

e. In human engineering, an "optimal" work condition often is one in which an operator undergoes as little physical strain as possible, so that he can perform his task for a long time without deterioration.

f. In many cases, force or torque capability is not limited by the muscular capacity but by the reaction force generated by body weight, body support and body posture. Human strength applications depend on the spatial relations between control and operator and how the body support available to the subject affects the amount of force or torque he can develop.

g. Stereotypical response and dexterity patterns may be fundamentally different between populations and hard to change.

h. As a rule of thumb, 10% of a given population is left handed.

i. It has been shown that while the absolute forces exerted by men and women vary characteristically, the relationships between location, body position and exerted strength are similar for both sexes.

j. Biomechanically advantageous position is one in which the upper arms are normally vertical or slightly elevated and the elbow angle should be near 90 degrees,

k. Less than 20% of total strength can be maintained over practically indefinite periods of time without deterioration due to fatigue. This 20th percentile is one of the most important cutoff values in design for strength. In military, 5th (or 3rd) percentile is used for the lower limit. Assuming normal distribution, percentile factors are calculated as "mean +/- α times one standard deviation"; where α = 1.65 (5th, 95th), 1.88 (3rd, 97th), 2.33 (1st, 99th), 1.28 (10th, 90th), 0.84 (20th, 80th), 0.65 (25th, 75th) or 0 (50th, mean).

l. The biomechanical principles of the human body are the same for all populations. Hence, a design for selected ranges of dimensions of joint angles and of body positions applies to all user populations (sex and nationality).

5. Laubach LL. "Comparative muscular strength of men and women: A review of the literature." Aviat. Space Environ. Med. 47:534-42, 1976. Also see Laubach LL. "Muscular strength of men and women: A comparative study." Wright Patterson Tech Report AMRL-TR-75-32, May 1976. (DTIC #AD-A025 793)

Laubach reviewed nine separate studies. Overall, female upper extremity strength was 35 to 79% of men's (mean 55.8%); female lower extremity strength was 57 to 86% of men's (mean 71.9%); female trunk strength was 37 to 70% of men's (mean 63.8%); and dynamic strength indicators: females were 59 to 84% as strong as males (mean 68.6%). To estimate percentiles, he multiplied 1.65 times the standard deviation of the individual measurement and subtracted (added to) this value from the mean for 5th (95th) percentiles. (Note that 1 kilopond = 1 kilogram force = 9.807 N; 1 lbf (pound force) = 4.448 N.)

Median dynamic strength measurements:

pushing:	men:	36.3 kp =	356.0 N =	80.0 lbf	
pushing:	women:	27.7 kp =	271.7 N =	61.1 lbf	(76% of men)
pulling:	men:	31.8 kp =	311.9 N =	70.1 lbf	
pulling:	women:	26.8 kp =	262.8 N =	59.1 lbf	(84% of men)

Summary of mean cable tension (calibrated cable tensiometer) and hand grip (Smedley adjustable hand dynamometer) strength values (female data from 31 college students with similar physical characteristics to USAF females):

Shoulder flexion:

men:	50.1 kp =	491.3 N =	110.5 lbf	
women:	22.6 kp =	221.6 N =	49.8 lbf	(45% of men)

Elbow flexion:

men:	57.2 kp =	561.0 N =	126.1 lbf	
women:	25.2 kp =	247.1 N =	55.6 lbf	(44% of men)

Hip flexion:

men:	62.6 kp =	613.9 N =	138.0 lbf	
women:	50.9 kp =	499.2 N =	112.2 lbf	(81% of men)

Knee extension:

men:	102.8 kp =	1008.2 N =	226.7 lbf	
women:	58.8 kp =	576.7 N =	129.6 lbf	(57% of men)

Trunk flexion:

men:	90.9 kp =	891.5 N =	200.4 lbf	
women:	33.8 kp =	331.5 N =	74.5 lbf	(37% of men)

Grip strength:

men:	50.4 kp =	494.3 N =	111.1 lbf	
women:	26.4 kp =	258.9 N =	58.2 lbf	(52% of men)

Additional grip strength values (results from 5 different studies):

men:	55.9 kp =	548.2 N =	123.2 lbf	
women:	37.5 kp =	367.8 N =	82.7 lbf	(63% of men)
men:	55.0 kp =	539.4 N =	121.3 lbf	
women:	29.8 kp =	292.2 N =	65.7 lbf	(61% of men)

PUSH forces:

Forward push with both hands (reaction force provided by floor and footrest)

men:	63.6 kp =	623.7 N =	140.2 lbf	
women:	23.9 kp =	234.4 N =	52.7 lbf	(37% of men)

Lateral push with the shoulder (reaction force provided by floor and footrest)

men:	87.1 kp =	854.2 N =	192.0 lbf	
women:	38.8 kp =	380.5 N =	85.5 lbf	(45% of men)

Forward push with both hands (reaction force provided a vertical wall)

men:	130.9 kp =	1283.7 N =	288.6 lbf	
women:	56.1 kp =	550.2 N =	123.7 lbf	(37% of men)

Backward push (reaction force provided a vertical wall)

men:	194.0 kp =	1902.6 N =	427.7 lbf	
women:	68.8 kp =	674.7 N =	151.7 lbf	(35% of men)

Lateral push with one hand (reaction force provided a vertical wall)

men:	76.0 kp =	745.3 N =	167.6 lbf	
women:	32.5 kp =	318.7 N =	71.7 lbf	(43% of men)

Forward push with one hand (reaction force provided a vertical wall)

men:	53.1 kp =	520.8 N =	117.1 lbf	
women:	25.0 kp =	245.2 N =	55.1 lbf	(47% of men)

Additional Static measurements:

Neck flexion forward (results from 2 different studies):

men:	13.8 kp =	135.3 N =	30.4 lbf	
women:	8.4 kp =	82.4 N =	18.5 lbf	(62% of men)

Vertical pull downwards (results from 2 different studies):

men:	56.8 kp =	557.0 N =	125.2 lbf	
women:	35.3 kp =	346.2 N =	77.8 lbf	(62% of men)
men:	61.6 kp =	604.1 N =	135.8 lbf	
women:	27.8 kp =	272.6 N =	61.3 lbf	(54% of men)

Vertical push upwards (results from 2 different studies):

men:	23.7 kp =	232.4 N =	52.3 lbf	
women:	13.8 kp =	135.3 N =	30.4 lbf	(58% of men)

Horizontal pull (results from 2 different studies):

men:	46.5 kp =	456.0 N =	102.5 lbf	
women:	29.3 kp =	287.3 N =	64.6 lbf	(63% of men)
men:	41.1 kp =	403.1 N =	90.6 lbf	
women:	25.0 kp =	245.2 N =	55.1 lbf	(61% of men)

Horizontal push (results from 2 different studies):

men:	32.1 kp =	314.8 N =	70.8 lbf	
women:	20.7 kp =	203.0 N =	45.6 lbf	(64% of men)
men:	37.3 kp =	365.8 N =	82.2 lbf	
women:	18.7 kp =	183.4 N =	41.2 lbf	(50% of men)

Elbow flexion (results from 4 different studies):

men:	57.0 kp =	559.0 N =	125.7 lbf	
women:	25.0 kp =	245.2 N =	55.1 lbf	(44% of men)
men:	30.1 kp =	295.2 N =	66.4 lbf	
women:	16.4 kp =	160.8 N =	36.2 lbf	(54% of men)

Elbow extension (results from 2 different studies):

men:	19.2 kp =	188.3 N =	42.3 lbf	
women:	10.0 kp =	98.1 N =	22.1 lbf	(52% of men)

Hand volar flexion (results from 3 different studies) (moments are listed):

men:	81.4 kp cm	
women:	56.4 kp cm	(69% of men)
men:	78.6 kp cm	
women:	54.1 kp cm	(59% of men)

Hand dorsal extension (results from 3 different studies) (moments are listed):

men:	103.6 kp cm	
women:	70.5 kp cm	(68% of men)
men:	109.4 kp cm	
women:	62.5 kp cm	(57% of men)

Handle pronation (results from 3 different studies) (moments are listed):

men:	144.1 kp cm	
women:	87.4 kp cm	(61% of men)
men:	142.0 kp cm	
women:	66.5 kp cm	(47% of men)

Handle supination (results from 3 different studies) (moments are listed):

men:	152.7 kp cm	
women:	88.3 kp cm	(58% of men)
men:	128.0 kp cm	
women:	58.2 kp cm	(45% of men)

In order to use these data to estimate the female fifth percentile design criteria, do the following:

1. Select a test item that most closely approximates the strength movement you are studying and use the percentage difference in your calculations, e.g. 69% from hand volar flexion

2. Assume, for example, that the data you have from male subjects yields a mean of 80 kp cm ± 25 kp cm (one standard deviation, S.D.)

3. To calculate the estimated fifth percentile value for men multiply 1.65 times 25 kp cm (S.D.) to give 41.3 kp cm. Subtract 41.3 kp cm from the 80 kp cm (mean) to give 38.7 kp cm for the estimated fifth percentile for men.

4. Take the fifth percentile estimate for men, 38.7 kp cm, and multiply by the percentage difference, 69%, to give 23.6 kp cm for the estimated fifth percentile for females.

According to Laubach, it has been shown that the percentage differences between female and male strength are, in general, similar at the fifth percentile, mean and 95th values.

6. Laubach LL, McConville JT, Churchill E, White RM. "Anthropometry of women of the US Army - 1977. Report number 1. Methodology and survey plan." Natick Technical Report NATICK-TR-77/021, Webb Associates, Inc., Yellow Springs Ohio, June 1977. (DTIC #AD-A043 715) and

Churchill E, Churchill T, McConville JT, White RM. "Anthropometry of women of the US Army - 1977. Report number 2. The basic univariate statistics." Natick Technical Report NATICK-TR-77/021, Webb Associates, Inc., Yellow Springs Ohio, June 1977. (DTIC #AD-A044 806) and

Tebbetts I, Churchill T, McConville JT. "Anthropometry of women of the US Army - 1977. Report number 4. Correlation coefficients." Natick Technical Report NATICK-TR-77/021, Webb Associates, Inc., Yellow Springs Ohio, Feb 1980. (DTIC #AD-A084 119)

This is a widely quoted anthropometric survey of US Army women. The first report includes the anthropometry definitions, the survey plan and nine static strength tests. These included a long handle (45 cm), short handle (15 cm), "D" ring and rope, force monitor and platform. The grips had 2.5 cm diameters and were covered with tape. They measured a 3 s average (interval beginning 2 s after the force reached a minimum 10 lbf, provided that at this time the force still exceeded the minimum) and peak values. Each measurement was repeated twice. Reports 2 and 4 contain the pertinent results for this report. The values that follow are the mean and 5th percentile (5th %) values (lbf) from the two sets of measurements.

a. Standing Two Handed Pull with long handle 38 cm above platform. The subject stood with her feet 45 cm apart and knees bent. She bent at the waist and grasped both sides of the long handle. She was instructed to minimize pull with back and, while bent at waist and knees, pull the handle with arms and shoulders and using her legs by extending them upwards during pull.

a. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	124.8 ± 33.6	128.5 ± 33.2	71.2	74.4
Peak Force	139.6 ± 35	143.5 ± 33.5	82.9	89.2

b. Standing Two Handed Pull with long handle 50 cm above platform (straight knee). The subject stood with her feet 45 cm apart and knees straight. She bent at the waist and grasped both sides of the long handle. She was instructed to minimize the pull with the back and, while bent at waist, pull handle with arms and shoulders and using her legs by extending them upwards during pull.

b. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	122.9 ± 35.9	129.6 ± 35.3	64.7	73.3
Peak Force	137.1 ± 37	144 ± 36.1	76.3	84.1

c. Standing Two Handed Pull with long handle 100 cm above platform. The subject stood erect with her feet 45 cm apart and grasped both sides of the long handle. The subject pulled the handle using her arms, keeping knees straight and feet firmly planted on the platform.

c. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	68.4 ± 17.9	67.8 ± 17.7	41.5	41.6
Peak Force	76.3 ± 18.6	76.2 ± 19	48.2	49

d. Standing Two Handed Push with long handle 150 cm above platform. The subject stood erect with her feet 45 cm apart and grasped both sides of the long handle from below. The subject pushed the handle straight up using arms and shoulders, keeping knees straight and feet firmly planted on the platform.

d. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	57.1 ± 15.6	57.3 ± 16.1	33.8	38.4
Peak Force	65.2 ± 17.2	65.9 ± 17.5	40.2	42.2

e. Standing One Handed Pull with "D" ring 100 cm above platform. The subject stood erect with her feet 15 cm apart and flat on the platform. She stood to one side of the hook so that she grasped the "D" ring from underneath with her dominant hand and the rope was parallel to the long axis of the adjacent leg. The other arm was relaxed at her side. The subject pulled the "D" primarily using her arm, while keeping shoulders square, knees straight and feet firmly planted on the platform.

e. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	41.8 ± 12.7	41.4 ± 13.4	23.0	23.1
Peak Force	48.9 ± 14.2	48.6 ± 14.9	29.3	29.6

f. Seated One Handed Pull with "D" ring 45 cm above platform just forward of the seat and in the centerline of seat. The subject sat erect with her feet 55 cm apart and flat on the platform. The chair was positioned behind the platform hook so that the rope attached to the "D" was vertical when pulled. She grasped the "D" ring from the underside with her dominant hand without bracing her arm on her thigh. The other arm rested in her lap. The subject pulled the "D" primarily using her arm, while keeping shoulders square, knees straight and feet firmly planted on the platform. She did not grasp under the chair with the other hand.

f. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	49.9 ± 19.7	50.9 ± 20.1	23.9	22.8
Peak Force	58.8 ± 22.5	59.7 ± 22.3	28.5	28.6

g. Seated One Handed Pull with "D" ring 45 cm above platform on the side of the seat. The subject sat erect with her feet 55 cm apart and flat on the platform. Chair was positioned so that the platform hook was a short distance to the dominant side of a point midway between the maximal protrusion of the buttock and knee. She grasped the "D" ring from the underside with her dominant hand. The other arm rested in her lap. The subject pulled the "D" primarily using her arm, while keeping shoulders square and feet firmly planted on the platform.

g. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	47.1 ± 15.8	48 ± 15.6	24.5	23.9
Peak Force	55.4 ± 18	56.3 ± 17.4	30.2	30.1

h. Seated Two Handed Pull with short handle 38 cm above platform just forward of the seat and in the centerline of seat. The subject sat erect with her feet 55 cm apart and flat on the platform. Chair was positioned behind the platform hook so that the rope was vertical when pulled. The subject bent slightly at the waist and grasped both sides of the handle with her hands. The subject lifted the handle primarily using her arms and shoulders while keeping hers arms off her thighs.

h. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	105 ± 35.2	108.5 ± 36.1	51.4	54.3
Peak Force	118. ± 36.7	122.3 ± 37.9	61.8	64.0

i. Seated Two Handed Pull with short handle 50 cm above platform just forward of the seat and in the centerline of seat. Same procedure as h.

i. lbf ± 1 SD	Mean #1	Mean #2	5th % #1	5th % #2
Mean Force	87.8 ± 28.6	89.9 ± 29	44.0	45.9
Peak Force	99.6 ± 30.7	101.3 ± 31.5	53.3	53.2

No correlation coefficients were found greater than 0.36 (most around 0.1) between sitting strength measures and anthropometry data. Standing correlation values were a bit higher, up to 0.55. For example, when the seated center pull was compared with the side pull: r = 0.76 for average force, r = 0.79 for peak force; with two handed 38 cm pull: r = 0.63 for average force, r = 0.59 for peak force; with two handed 50 cm pull: r = 0.58 for average force, r = 0.58 for peak force. When the seated side pull was compared with the two handed 38 cm pull: r = 0.59 for average force, r = 0.59 for peak force; with two handed 50 cm pull: r = 0.57 for average force, r = 0.59 for peak force. When the seated two handed 38 cm pull was compared the two handed 50 cm pull: r = 0.71 for average force, r = 0.70 for peak force.

7. Human engineering guide to equipment design. eds. Morgan CT, Cook, III JS, Chapanis A, Lund MW. New York:McGraw Hill Book Co., Ch. 11, 1963.

The following summarizes pertinent information from Chapter 11 concerning strength studies.

Muscular force depends on two factors. The first factor is muscle tension (contractile force), which "reaches a maximum when the length is greatest and there is momentarily no change in length." Tension decreases as the muscle shortens and as its rate of shortening increases. The second is the mechanical advantage of the body's lever system in which the long bones are the lever arms and the joints are the fulcra. Power is applied at the points of muscle attachment. Both factors vary with changes in the angle of the joints. Other factors affecting strength include age (maximum in middle to late 20's, 90-95% max at 40 yrs, 85% at 50, 80% at 60, though not all strengths decline at this rate, e.g. back strength falls more rapidly) body build, body position and handedness. Strength decreases with altitude (due to reduced oxygen supply) depending upon individual variability and acclimatization. Fully acclimatized persons

have been shown to maintain sea level grip strength up to 13,000 ft, it then decreases slowly up to 16,500 ft, then it remains fairly constant until 23,000 ft at which point a more rapid decline begins. Brief exertions are less affected by altitude than muscular endurance. Endurance time for moderate to heavy activity begins to decline at 6,500 ft and at 20,000 ft (even if acclimatized) endurance is 50% of sea level values. Note that mountain climbers have ascended up to 28,000 ft or higher without oxygen supplements. Occupational factors such as the type of clothing worn affects strength. The use of backrests on seats increases pushing strength and footrests increase pulling strength. Restraining harnesses or seat belts generally increase pulling strength but, by restricting movements, may prevent attaining the most efficient positions for other types of efforts such as lifting with leg and back muscles.

The authors caution that performance at or near the limits of physical abilities should not be required because fatigue will develop rapidly and actual injury might occur (muscle sprain or rupture, strained or torn ligaments).

Tables 1 through 4 contain isometric forces measured from male subjects manipulating an aircraft center control stick (forward, aft, left and right directions). Corresponding values for females are given based on the method of Laubach (1976).

Control distance from SRP	Control distance from midplane	5th Male	50th Male	95th Male	5th Female	50th Female	95th Female
9"	0	26	46	67	15	26	38
	4.5" left	18	33	54	10	19	31
	8" left	12	29	44	7	17	25
	4.5" right	34	58	82	19	33	47
	8" right	37	65	95	21	37	54
12.5"	8" left	18	36	68	10	21	39
	8" right	43	74	102	25	42	58
15.5"	0	43	86	160	25	49	91
	8" left	23	60	118	13	34	67
	8" right	53	100	164	30	57	93
18.75"	0	64	124	177	36	71	101
	8" left	36	72	114	21	41	65
	8" right	70	125	198	40	71	113
23.75"	0	54	106	141	31	60	80
	8" left	29	64	104	17	36	59
	8" right	56	100	147	32	57	84

Table 1. Maximum isometric force (lbf) exerted in PUSHING on an aircraft center control stick by the right arm of USAF males in a sitting position. Stick grasped 13.5" above SRP (seat reference point - midpoint of seatpan at junction between seatpan and seatback). Control distance from midplane of body: 4.5" is midway between midpoint at outer edge of thigh at 8". Values for female are estimates based on Laubach (1976) (57% of male). (Adapted from Morgan, et al. 1963)

Control distance from SRP	Control distance from midplane	5th Male	50th Male	95th Male	5th Female	50th Female	95th Female
9"	0	34	57	86	21	35	53
	4.5" left	28	45	66	17	28	41
	8" left	26	40	67	16	25	42
	4.5" right	39	62	88	24	38	55
	8" right	39	58	86	24	36	53
12.5"	8" left	33	53	77	20	33	48
	8" right	49	80	108	30	50	67
15.5"	0	54	83	113	33	51	70
	8" left	39	64	98	24	40	61
	8" right	55	89	119	34	55	74
18.75"	0	56	86	127	35	53	79
	8" left	45	74	108	28	46	67
	8" right	58	99	126	36	61	78
23.75"	0	62	102	138	38	63	86
	8" left	51	90	129	32	56	80
	8" right	58	103	133	36	64	82

Table 2. Maximum isometric force (lbf) exerted in PULLING on an aircraft center control stick by right arm of USAF males in a sitting position. Female values are estimates based on Laubach (1976) (62% of male). Notations are the same as in Table 1. (Adapted from Morgan, et al. 1963)

Control distance from SRP	Control distance from midplane	5th Male	50th Male	95th Male	5th Female	50th Female	95th Female
9"	0	30	47	66	13	20	28
	4.5" left	31	49	67	13	21	28
	8" left	24	44	65	10	18	27
	4.5" right	26	46	78	11	19	33
	8" right	26	44	72	11	18	30
12.5"	8" left	23	44	70	10	18	29
	8" right	22	39	59	9	16	25
15.5"	0	24	38	52	10	16	22
	8" left	20	35	58	8	15	24
	8" right	24	40	70	10	17	29
18.75"	0	8	32	53	3	13	22
	8" left	16	30	56	7	13	24
	8" right	22	39	70	9	16	29
23.75"	0	14	29	46	6	12	19
	8" left	11	21	49	5	9	21
	8" right	20	37	66	8	16	28

Table 3. Maximum isometric force (lbf) exerted to the LEFT on an aircraft center control stick by right arm of USAF males in a sitting position. Female values are estimates based on Laubach (1976) (42% of male). Notations are the same as in Table 1. (Adapted from Morgan, et al. 1963)

Control distance from SRP	Control distance from midplane	5th Male	50th Male	95th Male	5th Female	50th Female	95th Female
9"	0	23	38	49	10	16	21
	4.5" left	31	48	64	13	20	27
	8" left	34	55	74	14	23	31
	4.5" right	15	27	51	6	11	21
	8" right	12	22	43	5	9	18
12.5"	8" left	31	48	70	13	20	29
	8" right	16	24	46	7	10	19
15.5"	0	20	28	39	8	12	16
	8" left	25	43	63	11	18	26
	8" right	13	22	49	5	9	21
18.75"	0	15	25	35	6	11	15
	8" left	22	36	61	9	15	26
	8" right	14	24	50	6	10	21
23.75"	0	13	20	30	5	8	13
	8" left	19	31	48	8	13	20
	8" right	12	22	51	5	9	21

Table 4. Maximum isometric force (lbf) exerted to the RIGHT on an aircraft center control stick by right arm of USAF males in a sitting position. Female values are estimates based on Laubach (1976) (42% of male). Notations are the same as in Table 1. (Adapted from Morgan, et al. 1963)

8. McCormick EJ. Human factors engineering., 3rd ed. New York:McGraw Hill Book Company, Ch 10, 1970.

The following summarizes pertinent information from Chapter 10 concerning strength studies.

Push and pull movements are the strongest, as compared to up, down, in, out, right or left, with the strongest positions being at angles of 150° and 180°. Up and down movements are a bit stronger at 120° and 90° and out movements are the weakest. The extent of muscular endurance is relative in that a weak person can maintain 50% of their own strength level about as long as a stronger person can maintain 50% of their strength. Elbow flexion action is about half again as strong as an extension action, with the greatest flexion force possible when the elbow is at about a right angle. Shoulder actions are generally stronger than elbow actions. In a seated position, shoulder extension (upward push) is more forceful than flexion (downward pull). Maintaining a static posture is generally more fatiguing than some kind of posture in which an individual can make adjustments.

McCormick provides the following information concerning reaction time. Physiological delays include receptor delays (1 - 38 ms), neural transmission to cortex (2 - 100 ms), central-process delays (70 - 300 ms), neural transmission to muscle (10 - 20 ms) and muscle latency and activation time (30 - 70 ms). The total delay, or reaction time, therefore ranges from 113 to 528 ms. This is in addition to the movement time of the limb itself. For most control activities, a minimum of 300 ms is required along with a reaction time of 200 ms, comprising a total response time of 500 ms. This depends on the nature of the motion as well as the complexity of the task, including the number of choices. For example, for a pilot flying an 1,800 mph aircraft, the total time to initiate a control sequence change in response to suddenly sighting another aircraft can be as long as 1.7 s (0.3 s for visual acquisition, 0.6 s for recognition of impending danger, 0.5 s to select course of action and 0.3 s to initiate the desired control response). Given the response time of the aircraft, if the two planes were less than 4 miles apart, any response would be futile.

9. Caldwell LS. "The load-endurance relationship for a static manual response." <u>Human Factors,</u> 1964; 6:71-9.

64 male college students were tested for maximal pull capabilities at two fixed elbow angles (80° and 150°) with a fixed shoulder angle and relationship to the handle. For endurance trials, during which the subjects performed a sub-maximal hold, subjects monitored their performance with a voltmeter and green and red lights. Whenever the applied force was less than required, the red light was illuminated and when force equal to or greater than that required, the green light was illuminated. The subjects were instructed to keep green light lit as long as possible. The inclusion of lights was necessary because the subjects had difficulty attending to the voltmeter as they approached their endurance limits. Subjects were given two practice sessions for maximum strength and endurance trials during which the lights were set to half of an individual subject's maximum strength and told to pull just hard enough to keep green light lit. Endurance sessions were terminated when the output fell below the required level and the subject could not relight the green lamp after three seconds.

Muscular endurance was measured at 50%, 60%, 70% and 80% of the maximum pull for a given subject at the two elbow angles. Since this was a relative loading task, the actual forces were quite different among subjects. Two trials were held per day over four days with a 20 min rest allowed between individual trials and 24 hours minimum rest between daily sessions.

At the 80° elbow angle, mean strength was 114.6 ± 17.9 lbf, ranging from 79 to 190 lbf; at the 150° elbow angle, mean strength was 162.0 ± 26.0 lbf ranging from 117 to 238 lbf. Mean endurance was 42.8 s at the 80° elbow angle and 39.5 s at the 150° elbow angle. However, when Caldwell factored in the actual (not relative) applied force, endurance was found to be greater at 150°. The mean endurance for both angles was: 64 s at 50% of maximum, 48 s at 60% of maximum, 33 s at 70% of maximum and 22 s at 80% of maximum. To examine the effects of extremes of strength, the strongest (greater than 1 standard deviation from the mean) vs weakest (less than 1 standard deviation from the mean) mean difference between endurance functions (time vs relative load) was 1.3 s. The author also calculated force times endurance, where force was the value maintained at each relative load times time. The author stated that while strength may be related to arm dimensions, stature and weight, endurance time was not.

10. Caldwell LS. "Body stabilization and the strength of arm extension." <u>Human Factors,</u> 1962: 4:125-30.

Nine subjects (gender unspecified) were measured to determine maximum force generated during arm extensions (push) at five elbow angles (60°, 85°, 110°, 135°, 160°) with five conditions of back support (no support or support at 20, 40, 60 and 80% of the distance from the seat to the height of the shoulder joints). Subjects performed two trials at each combination of back support height and elbow angles. Trials lasted seven seconds during which subjects were to reach their maximum output after 3s to avoid "slam", between each trial was a 60 s rest period (subject instructed to better second trial) and a 3 min rest period was allowed between successive pairs of trials. The strength response was influenced by the elbow angle and the extent of body stabilization provided by the back support. Backrest height had little effect at lesser elbow angles but at 135° and 160° (the angle in which the highest forces were measured), the higher back supports served to stabilize the mechanical level system of the arm and shoulder thereby allowing the highest generated push force (60% at 160° was the most effective combination).

11. Caldwell LS. "Body position and the strength and endurance of manual pull." <u>Human Factors,</u> 1964; 6:479-84.

Strength and the duration of a submaximal holding response (endurance) was measured in ten subjects at twenty body positions (5 elbow angles [95°, 110°, 125°, 140°, 155°], 2 thigh angles [0°, 20°] and two

knee angles [110°, 150°]). The objective was to determine if the assumption that the body and control position that is associated with the greatest generated isometric force will also lead to the longest endurance time. Trials were conducted in pairs: an eight second maximal pull, followed by a three minute rest, then an endurance trial at 80% of mean maximum strength (based on five practice sessions). Two sessions were held per day with four hours between sessions. It was found that as the thigh angle increased, the force developed by the legs tended to increasingly to wedge the subject into his seat and improved trunk stabilization. An increase in knee angle both increased the output of the toggle (mechanical toggle which produced a compressive force between the control and the backrest) and improved body stabilization while an increase in thigh angle only improved stabilization. Strength was enhanced as body stabilization was improved by either increasing thigh elevation or straightening the leg and strength was improved as arm was straightened. Endurance time was improved at the 20° thigh angle (3.3 s, $p < 0.01$), at the 150° knee angle (2.7 s, $p = 0.05$) and time increased from 24.4 s to 40.4 s as the elbow angle increased from 95° to 155° ($p < 0.01$).

12. Caldwell LS. "Decrement and recovery with repetitive maximal muscular exertions." Human Factors, 1970; 12:547-52.

This study investigated how strength was effected by comparing successive decrement and recovery functions in a repetitive task and to test the hypothesis that with repeated trials recovery becomes independent of the inter-trial interval (i.e., rest). Pull strength of sixty Army males was tested using a standard position (150° elbow angle, 150° knee angle and a 20° elevation of the thigh). Practice was three 5 s trials in which they performed a maximal pull followed by 5 min rest - they were instructed to put their entire body into it by pushing with their feet. Data sessions included ten 12.5 s trials separated by 12.5, 25, 50, 100 or 200 s (a constant interval within a session). Timers were set and subjects were told that 3 s prior to pulling the handle a buzzer would sound and to get into position and pull as hard as possible when a display lamp went on. Sessions were at least 24 hr apart. Scores were determined after 3, 6, 9 and 12 s into the pull. Mean strength was also determined (average of four scores per trial), the decrement in each trial (last score subtracted from the first) and recovery during rest (last score in a trial subtracted from the first score of the following trial). Scores were normalized by dividing by the maximum strength obtained in preliminary trials.

It was found that the decrement in output was inversely related to recovery time. There was a larger initial decrease then, after the third or fourth trial, there was essentially a linear decrease in output. The effect of rest duration on decrement was small with a difference of 2% between means for the 12.5 and 200 s conditions. For short rests, strength decrements were variable. With long rests, there was an essentially linear decline over trials. For short rests, recovery strength tended to increase with successive rests but for long rests, the tendency was for recovery strengths to decrease after repeated rests. In sum, it was found that the amount of strength recovery with rest was influenced by the length of rest as well as the degree to which the response was degraded by prior performance.

Even with long rest periods, there was evidence of rapid onset of fatigue and slow recovery. Isometric "work" was more costly in terms of the amount of decrement and recovery time. When contraction strength was 70% or more of maximum there was an effective occlusion of the blood vessels in the active muscles. This led to rapid depletion of local energy stores and quickly mounting pain. The ischemic pain might have become so bothersome that output may have been reduced due in part to withdrawal reactions. Isotonic contractions with alternating muscle contraction and relaxation served to provide a mechanical pumping action to eliminate metabolic wastes and provide fresh blood supplies. (See Smith, et al (1968))

13. Smith LE, Edwards DK. "Prediction of muscle endurance (work performance) from individual differences in initial and post training increments in static strength." Human Factors, 1968; 10:345-50.

Forty college men were tested for isometric strength (hand grip) and endurance prior to an isotonic strength training program. To assess static strength, subjects performed five maximal contractions with a 2 minute rest between each. Subjects were seated with their nonpreferred hand holding the table for stabilization. Isometric endurance was determined by the subject sustaining a 2 minute maximum isometric contraction, then they relaxed their grip for 250 ms, then performed one rapid contraction. This was followed by 10 maximal 2 s contractions with one minute rests in between. Subjects watched the recording device output and were continually encouraged to maintain their grip exertion. Isotonic endurance was assessed by having subjects perform a six minute alternating maximal grip-rest- grip-rest cycle. Working with metronome, an investigator gave the following command repetitively, "squeeze-hold-rest-rest" during a 4 s cycle, i.e. maximal contraction for 2 s followed by 2 s rest. Subjects were allowed to practice to get timing while only lightly gripping the dynamometer. The authors stated that no clear correlation was found between the increases in static strength performance after training and subsequent hand grip endurance.

II. MUSCULAR STRENGTH ASSOCIATED WITH MANIPULATION OF AIRCRAFT CONTROLS

1. Chambers RM. "Control performance under acceleration with side-arm attitude controllers." NADC Report No. NADC-MA-6110, 27 Nov., 1961.

Seven different side-arm stick controllers were examined in this study. Subjects were trained statically (1 g) at NASA on one, two and four stage launch profiles. Closed loop dynamic flight simulation was conducted at the Naval Air Development Center (NADC) with loads up to +15 Gx. To judge performance, mean integrated error in radian seconds for flight path, nozzle deflection angle in pitch, roll error and yaw error, also angle of attack and altitude were measured. No conclusive differences between the controllers was reported, however, there were breathing difficulties and visual impairments (including tearing, focus, keeping eyes open). Also there was a tendency to over control at higher Gx. Performance of moveable sticks deteriorated at higher Gx. Wrist motions were more difficult under dynamic vs static conditions. Varying vehicle characteristics in terms of stability and damping were also investigated.

Reentry piloting tasks were also simulated. These entailed maintaining a specific angle of attack, making step changes in angle of attack when deceleration reached certain levels, maintain a constant descent rate, change descent rate from an initial value and hold it, level off at a certain G level, maintain zero error on angle of attack error meter and to damp out oscillations.

The author provided this list of control stick characteristics which may influence performance under G:

1. stick force gradients along each mode of control
2. centering characteristics along each mode of control
3. break-out force
4. control friction
5. damping characteristics
6. control throw
7. control response time
8. control harmony
9. cross coupling
10. control feedback
11. control sensitivity

Under G-loads one must also consider the following items when designing controls: the pilot restraint system, the position of controller relative to the pilot and the number and location of the axes of motion relative to the pilot and the acceleration field.

2. Chambers RM., Hitchcock, Jr. L, Schmidt CF. "Effects of acceleration on pilot performance." NADC Report No. NADC-MA-6219, 26 March, 1963.

In this subsequent report, the authors offer this expanded list of control stick characteristics which may influence pilot performance while exposed to G-stresses:

1. relationship between the axes of controller motion and the acceleration vectors imposed upon the pilot's hand
2. number of axes of motion
3. stick force gradient along each mode of control
4. centering characteristics along each mode of control
5. control location
6. controller break-out forces
7. control device friction
8. damping characteristics
9. magnitude of the control throw
10. control response time
11. control harmony
12. cross coupling
13. amount of kinetic feedback provided by the controller
14. controller shape and size
15. dynamic and static balancing of the control device

3. Laubach LL, Kroemer KHE, Thordsen ML. "Relationships among isometric forces measured in aircraft control locations." Aerospace Med. 1972; 43:738-42. Also see Thordsen ML, Kroemer KHE, Laubach LL. "Human force exertions in aircraft control locations." Wright Patterson AFB:Aerospace Medical Research Lab, Technical Report AMRL-TR-71-119, Feb 1972. (DTIC# AD-740 930)

Fifty one males were used to measure peak isometric forces on six locations of hand-operated aircraft controls. The authors found that "... the amount of force exertable depends decidedly on the location of the control and on the direction of force exertion. ... Forces must be determined experimentally rather than by regression analysis ..." due to low correlation values. They also recorded the forces applied involuntarily at the same time as the requested force in a plane perpendicular to the required direction. In some cases the orthogonally applied force was actually larger than the requested direction.

Subjects sat unrestrained with support from seat back, sides and foot rest. They received specific instructions concerning the type, manner and directions of exertions required. All exertions were randomized with respect to control, direction and location of handle. No repetitions were required unless a maximal exertion was not made on first attempt. No talking or verbal encouragement was given during the test. After each exertion, the subject was told the magnitude that he generated. In Table 5, forces measured on a center control stick are given - Table 6 contains forces measured on a sidearm controller. Female mean isometric forces were estimated based on the mean dynamic strength values (69%) reported in Laubach LL. "Comparative muscular strength of men and women: A review of the literature." Aviat. Space Environ. Med. 47:534-42, 1976. 5th percentile forces were estimated based on the technique outlined in Laubach (1976).

Direction	Mean ± S.D. (male)	Range (male)	Estimated female force: Mean	5th percentile
Forward	68.8 ± 20.4	27 → 136	47.5	24.3
Backward	77.8 ± 13.8	48 → 114	53.7	38.0
Backward with inward push	69.1 ± 19.9	30 → 112	47.7	25.0
Backward with 2 hands	156.2 ± 19.4	100 → 198	107.8	86.7
Left	55.2 ± 11.9	28 → 91	38.1	24.5
Right	66.3 ± 14.3	33 → 103	45.7	29.5
Up	63.3 ± 14.4	27 → 87	43.7	27.3
Down	92.3 ± 25.4	33 → 131	63.7	34.8

Table 5. Mean ± 1 standard deviation (S.D.) and range of forces (lbf) applied by males to a center control stick moved in various directions. (Adapted from Laubach (1972)). Female forces are estimates based on values found in Laubach (1976).

Direction	Mean ± S.D. (male)	Range (male)	Estimated female force: Mean	5th percentile
Forward, handle vertical	157.7 ± 34.8	45 → 229	108.8	69.2
Forward, handle horizontal	148.2 ± 30.9	61 → 230	102.3	67.1
Backward, handle vertical	105.0 ± 16.6	46 → 140	72.5	53.6
Backward, handle horizontal	103.0 ± 16.9	54 → 139	71.1	51.8
Left	26.1 ± 9.9	12 → 56	18.0	6.7
Right	42.6 ± 9.3	17 → 64	29.4	18.8
Up	41.8 ± 13.3	17 → 83	28.8	13.7
Down	58.5 ± 15.0	25 → 94	40.4	23.3

Table 6. Mean ± 1 standard deviation (S.D.) and range of forces (lbf) applied by males to a sidearm controller moved in various directions. (Adapted from Laubach (1972)) Female forces are estimates based on values found in Laubach (1976).

4. McDaniel JW. Male and female strength capabilities for operating aircraft controls. AFAMRL Tech. Report No. AFAMRL-TR-81-39, 1981. (DTIC #AD-A098-256)

61 males and 61 females (conforming to USAF stature and weight requirements for pilots) wearing Nomex flying gloves and USAF flying boots applied maximal isometric exertions (4 s duration) in a stick control configured cockpit. This control was a stick-type aileron and elevator control and rudder pedals. After this assessment, half of the subjects performed an isometric and the other half an isotonic exercise regime over a nine week period. Both types of exercises employed handles and pedals. For the isotonic series, these handles and pedals moved levers and cables whereas for the isometric group, these were fixed. The subjects were retested after 3, 6 and 9 weeks of exercise. These controls are similar to those found in small trainer and transport aircraft. McDaniel reported the maximum exerted forces without specifying the stature and weight of the subjects. He specified a 5th, 50th (median) and 95th percentile range based on force alone. He referred to the 5th percentile as the "weaker" subjects. In Table 7, the descriptors "weaker", "median" and "stronger" are listed instead of his published percentiles to avoid

confusion with the rest of this report. They reported that the females were weaker than the males and a number of the females could not exert forces as specified in the MIL-F-8782B "Flying Qualities of Piloted Aircraft" design criteria. With both types of exercise, mean isometric strength increased without any clear difference between either the exercise type or gender of the subjects. The largest increase was with the rudder pedals and no difference was seen in lateral stick exertions (Table 8).

Control and direction	Male			Female		
	weaker	median	stronger	weaker	median	stronger
Stick Fwd	93	123	165	46	87	109
Stick Back	64	85	106	48	52	64
Stick Left	35	52	74	17	26	35
Stick Right	22	35	43	14	19	28
Left Rudder	170	450	700	160	260	460
Right Rudder	190	450	755	180	290	530

Table 7. Maximal forces exerted on control stick and rudder pedals (lbf) prior to exercise. (From McDaniel, 1981)

Control & direction	Exercise Type	Male Initial	Male after 9 wks	Female Initial	Female after 9 wks
Stick Fwd	Isometric	119	135	85	99
	Isotonic	132	142	84	86
Stick Back	Isometric	79	80	51	53
	Isotonic	91	94	52	51
Stick Left	Isometric	51	50	26	27
	Isotonic	56	56	27	28
Stick Right	Isometric	33	34	19	20
	Isotonic	35	38	20	22
Left Rudder	Isometric	402	450	277	380
	Isotonic	470	518	292	340
Right Rudder	Isometric	426	503	311	407
	Isotonic	486	558	320	373

Table 8. Mean forces exerted on control stick and rudder pedals (lbf) prior to and after nine weeks of exercise. (From McDaniel, 1981)

5. Kroemer KHE. "Effects of high G on pilot muscle strength available for aircraft control operation." Preprints of 1973 Annual Scientific Meeting of AsMA, May 7-10, 1973, pp 255-6.

Isometric strength was assessed in nine male subjects operating various aircraft controls at 1 g and at +3 and +5 Gz during open loop conditions. Maximal isometric force exertions were first determined in the lab as described in Thordsen, et al (1972). Subjects were seated in the gondola with their feet on a rigid footrest to standardize body position, wearing an anti-G suit, lap belt and shoulder harness. Two steel cylinders (1.5" diameter, 5" long, surface knurled) were placed in seven locations: center stick, aft stick, throttle, collective, sidearm controller, overhead control and panel control. Subjects applied a maximal exertion with left hand on each control in various directions. Subjects applied gradually increasing force until they reached their maximum then released the handle (2 - 5 s). Subjects applied force to one stick in one direction then, after a few seconds rest, to the opposite direction then repeated with the other stick at 1g, +3 and +5 Gz, then repeated after the gondola was brought to a stop. G levels, directions and sequences were randomized.

Stick movements were directed as follows: center stick moved forward, backward, left, right, up and down; aft stick moved forward and backward; throttle moved forward, backward, left, right, up and down; collective moved forward, backward, up and down; sidearm controller moved forward, backward, up and down; overhead control moved up and down; and panel control moved forward, backward, up and down.

They found that at higher +Gz-loads subjects exerted decreased horizontal forces along the x axis (e.g. forward at center stick). Exertion force applied with the +Gz-load was increased while force applied opposite to the +Gz-load decreased. Often the subjects could move hands and arms between control locations at +5 Gz. A summary of statistically significant differences is given in Table 9. Table 10 contains the center stick mean forces at 1g and at +3 and +5 Gz. Table 11 contains estimates of mean center stick forces for 5th percentile females based on the method of Laubach (1976).

Name & Direction	+3 Gz vs 1g	+5 Gz vs 1g	+5 Gz vs +3 Gz
Center Stick Forward	0	-	-
Center Stick Up	-	-	0
Center Stick Down	0	+	0
Throttle Right	0	0	-
Throttle Up	-	-	-
Throttle Down	+	+	+
Collective Up	-	-	-
Sidearm Up	-	-	-
Overhead Up	-	-	-
Panel Forward	-	-	0
Panel Up	-	-	-
Panel Down	+	+	+

Table 9. Summary of significant differences in exerted force under +Gz-stress. 0: no difference, -: significant reduction in applied force, +: significant increase in applied force. (From Kroemer, 1973)

Direction	1g Pre-test	3 Gz	5 Gz	1g Post-test
Forward	149 ± 40	140 ± 30	109 ± 30	139 ± 45
Backward	132 ± 30	139 ± 25	138 ± 29	129 ± 31
Left	44 ± 17	41 ± 27	47 ± 20	43 ± 19
Right	53 ± 14	51 ± 19	49 ± 13	57 ± 18
Up	44 ± 20	31 ± 19	31 ± 15	50 ± 19
Down	94 ± 29	60 ± 20	66 ± 23	92 ± 14

Table 10. Mean ± 1 standard deviation of force exerted on a center stick under +Gz-stress (lbf). (From Kroemer, 1973)

Direction	1g Pre-test	3 Gz	5 Gz	1g Post-test
Forward	56	61	40	43
Backward	55	65	60	52
Left	11	?	9	8
Right	47	40	18	45
Up	7	?	4	12
Down	31	18	19	46

Table 11. Estimated center stick forces (lbf) based on male values using the technique outlined in Laubach (1976) (-1.65 * sd + mean) by multiplying by 0.67 (standard 2/3 estimate). ?: estimate was 0. (From Kroemer, 1973)

6. Karim B, Bergey KH, Chandler RF, Hasbrook AH, Purswell JL, Snow CC. "A preliminary study of maximal control force capability of female pilots." CAMI Technical Report FAA-AM-72-27, Oklahoma City:Civil Aeromedical Institute, July 1972. (DTIC #AD-753 987)

The authors used isometric strength-duration curves to plot relative strength (percent of maximum strength vs endurance in minutes). Despite individual differences in maximum strength, the authors maintained that determining the relative loading per individual eliminated any differences in endurance among subjects. This curve took the form of a decaying exponential.

The authors operated under the following assumption. They measured maximal strength and strength/endurance curves to define the strength capabilities of the female pilot population in order to develop a load-endurance relationship. With this relationship, they stated that in the future all they needed to measure would be maximal strength and endurance could then be calculated from the curve.

Using a Convair-340 simulator, maximal voluntary effort for elevator push (right, then left arm), elevator pull (left), right aileron (left), left aileron (left) and rudders was measured in 25 female pilots. Strength vs endurance curves were calculated for elevator push (right) at 15, 30 and 45 pound loads, left aileron (left) at 10, 15, 25 pound loads, and left rudder (left leg) at 35, 70 and 105 pound loads. Subjects were tested in all control axes and the order was randomized. Maximal strength exertions lasted less than 10s, with no rest period (< 1 min). Age, height, weight, and upper arm, lower arm, upper leg and lower leg dimensions were measured. Also elbow angle, knee angle, foot angle and seat back height as a percentage of shoulder height were measured. For the endurance trials, subjects had three levels of force to maintain for each of three control axes with 5 min rests between exertions.

Subjects were instructed to adjust the seat to their normal flying position, then the safety belt was fastened. This non-standard posture was used in an attempt to measure actual strength capabilities as would be exerted in flight. Therefore, they obtained a wide range of operational strength values as opposed to values obtained in an artificial optimal posture. Subjects were repeatedly asked, "can you do any better?" during maximal strength tests. For endurance trials, subjects monitored a voltmeter and were told to hold the needle steady for as long as possible. During each trial a running conversation was held to keep their minds off the limb in use. Subjects were told how previous subjects had done and how they were performing. They tried to foster a spirit of competition to increase motivation. The mean maximal exertions are listed in Table 12.

Control Axis	Mean Max force	Maximum	Minimum
Elevator push (left)	69 ± 17	122	28
Elevator push (right)	73 ± 18	110	36
Elevator pull	72 ± 15	104	47
Right Aileron	33 ± 6	42	23
Left Aileron	30 ± 6	45	19
Right Rudder	177 ± 43	250	81
Left Rudder	178 ± 48	275	96

Table 12. Mean (± one standard deviation), maximum and minimum exertions (lbf) for female pilots tested in a Convair-340 simulator. (From Karim, et al., 1972)

They found that push strength increased as elbow angle increased for the positions tested. When asked to adjust their seats to a position similar to their normal flying position, they adjusted they seat relative to the rudder position. Right handed subjects were slightly stronger with their right hand than with the left. No difference was found in leg strength. These latter two findings were similar to those reported previously elsewhere.

They calculated a Strength Endurance Index for each subject and experimental condition for correlation analysis. The Index was equal to the product of endurance time (s) and relative load (percent of maximum). They correlated this Index with anthropometrics. Using this Index they obtained higher correlation values, but none greater than 0.5, though some were statistically significant.

7. Leeper RC, Hasbrook AH, Purswell JL. Study of control force limits for female pilots. Oklahoma City:Civil Aeromedical Institute, Technical Report FAA-AM-73-23, Dec 1973. (DTIC #AD-777 839)

In the follow up study, the authors repeated the force ranges from Karim, et al., (1972) while 24 female aviators performed piloting tasks. The subjects had to maintain needles in an artificial horizon and turn/bank indicators in the center of the displays while applying three exertions against three different load levels. Tests continued until the subject gave up or the display indicated that the subject had to endure a specific force outside the limits of a safe attitude. No subject recovered control once they went beyond that limit (10° roll and pitch at a turn rate of 2°/s). When the needle deviation reached half of the control limit the subject was reminded to center the display and at this point or greater deviation, they were given verbal encouragement. A seven minute limit was used (two minutes more than the point at which other investigators state that strength endurance can be continued indefinitely). Subjects adjusted the seat as in the Karim, et al., (1972) but had to hold the wheel in a specific manner. They also had to place the ball of their foot on a steel pipe attached to the surface of the pedal, placing the heel on a wooden box under the pedals. They were restrained by a seat belt and shoulder harness. They had two practice sessions at the low force level.

The authors provided a diagram describing the dimension related to the seat and controls, including
        a. vertical distance from the seat edge to the floor
        b. vertical distance from the wheel (center) to the seat edge
        c. horizontal distance from the seat back to the wheel at a + b distance.
        d. horizontal distance from the wheel to the rudder pedal
        e. vertical distance from the rudder to the floor
        f. angle from the seat back to the seat bottom
        g. angle from the seat bottom to the horizontal.
All dimension from the seat were taken with the cushion uncompressed.

8. Brown JL, Lechner M. "Acceleration and human performance. A survey of research." J. Aviat. Med. 1956; 27:32-49.

This review article reported on a study by Canfield in which the maximal force exerted by both arms on control stick to right, left, backward and forward directions up to +5 Gz (i.e. force directed perpendicular to G load) was measured. There were no significant changes in ability to perform either the forward push or backwards pull under +Gz-loads greater than 1g. Force exerted on the control stick to the right and left increased slightly but significantly with increased acceleration. Amount of force did vary considerably with the direction of application and arm position.

The authors also reported on a study by Wells and Morehouse in which acceleration was varied but total force on the control was held constant by having the subjects maintain a scale at a constant deflection (they measured EMG to monitor the force exerted). This was an attempt to separate exertion due to the applied force on stick from the component due to acceleration loading of the arm itself. They found that voluntary muscular exertion varied with acceleration in a manner which just offset the changes in force resulting from changes in arm weight due to the G-load.

To indicate a situation in which the G vector can act to overcome voluntary muscular effort, the authors reported a case in which a pilot could not actuate the pre-ejection lever under -Gz and was forced to eject through the canopy.

It was also found that the time to perform movements increased with increased acceleration up to 5 g (maximum level tested), with the greatest increase in time where the direction of movement was opposite to the acceleration vector.

Finally, the authors reported on a study of the ability to perform an ejection sequence. 5 of 30 subjects, protected with anti-g suits, failed to pull ejection seat face curtains when exposed to 2 G above their unprotected black-out level (GOR). Subjects were instructed in the most effective way to reach the handles and not all operationally required movements were included.

III.   GRIP STRENGTH

1. Ramakrishnan B, Bronkema LA, Hallbeck MS. "Effects of grip span, wrist position, hand and gender on grip strength." Proc. Human Factors & Ergonomics Soc 38th Annual Meeting, 1994; pp 554-8.

Static grip strength was determined for ten male and ten female college students (21 - 35 yr.) for three wrist positions: neutral, 45° flexion, 45° extension. Three hand dynamometer (Jamar Model 1) spans (3.5, 4.7, 6.0 cm) were tested. Using a standard anthropometric measuring kit (GPM - Swiss), forearm length, forearm circumference, wrist circumference, palm thickness, palm breadth, palm length and hand length were measured. Trials were conducted using the Caldwell regimen (1974). A restraint was used to position the arm at a 90° included elbow angle with the upper arm adducted with positions marked on the table for repeatable alignments.

They found that grip strength was 75 to 82% of that measured in the neutral position when the wrist was 45° extended. When the wrist was flexed 45°, grip strength was 60-72% of neutral. The authors stated that this was because the "ability of a musculotendinous unit to generate force is dependent upon its functional length." The strength of the non-dominant hand was 90 - 97% of dominant. And female grip strength ranged from 51 to 76% of males. Palm thickness and hand breadth was found to correlate with grip strength for non-dominant and dominant hands. At larger handle spans, forearm length was correlated with grip strength. Wrist circumference only correlated with the non-dominant hand with largest span. Female grip strength was 91% for smallest span, 75% of middle span and 68% of largest span as compared to the males. Overall, grip strength was greatest for largest span.

2. Grant KA. "Evaluation of grip force exertions in dynamic manual work." Proc. Human Factors & Ergonomics Soc 38th Annual Meeting, 1994; pp 549-53.

30 seated right handed males were tested while they performed a material transfer task. This involved grasping (power grip) and lifting a cylindrical aluminum handle from a location on the right side of a circular platform to a receptacle 42 cm away to the left (movement in two dimensions). The handle was tested at three weights: 0.65, 1.1 and 2.1 kg. The subjects also performed an assembly task which involved grasping and pulling downward on same aluminum handle, suspended 43 cm above the workstation on a rope which passed over a pulley. A weight loaded canister (1.1, 2.3 or 3.4 kg) tied to the other end of the rope provided rope tension as the handle was pulled down. After pulling down to a target position, subjects paused briefly and returned handle to its original position (movement in one dimension). One 2.5 min trial was conducted at each weight. During each trial subjects initiated movement of tool handle once very 5 s with a 3 min rest period between trials. Smooth motions were encouraged and practice was allowed. Grip force was measured with strain gauge in handle. Data was sampled at 175 Hz. Grip force was predicted based on a sinusoidal model.

They found that force exertion varied consistently in response to changes in grip force requirements (based on changes in the motion of the hand and handle) during dynamic manual tasks. Peak grip forces could significantly exceed mean levels or those predicted from static analyses. It was also found that the peak force occurred at the beginning of the movement with a tendency to "overshoot" required force, particularly at lower weights, possibly to prevent slipping.

IV.   CERVICAL STRENGTH

1. Foust DR, Chaffin DB, Snyder RG, Baum JK. "Cervical range of motion and dynamic response and strength of cervical muscles." SAE Paper 730975, Warendale, PA. 1973; pp. 285-308.

93 females and 87 males ranging in age from 18 to 74 were tested for range of motion, muscle reflex time and muscle strength (maximal voluntary strength) of the neck. Neck flexor and extensor EMG were recorded. The range of motion of the female cervical spine averaged 1-12 degrees greater than that of men, depending upon age (there was a degradation with increasing age). Average neck muscle reflex times ranged from 56-92 ms for flexors and 54-87 ms for extensors, with males generally slower reacting than the females. On the average, the stretch reflex was elicited at head accelerations at the c.g. between 0.3 to 0.5 g. Extensor muscles exhibited faster reflexes than flexor muscles, sometimes substantially faster. Deceleration time was slightly longer for extensors. However, extensors took longer to activate than flexors. This may be due to the fact that the neck extensors (semispinalis capitis, splenius capitis and various occipito-spinal and interspinal muscles) are relatively short and are layered deeply in the neck forming a complicated system. This is in contrast to the one primary neck flexor, the sternomastoid. It may simply have required more time for the neural control system to activate the larger extensor system. Males were on average stronger than females in both flexor and extensor strengths in every age and stature group tested. Table 13 contains the mean (± one standard deviation) force exerted by the neck flexors muscles and Table 14 contains similar information for the extensors.

Gender	Age	1-20th Percentile	40-60th Percentile	80-99th Percentile
Female	18-24	17.5 ± 2.9	20.5 ± 4.9	20.6 ± 6.7
	35-44	15.6 ± 4.0	18.8 ± 5.5	16.1 ± 3.5
	62-74	11.7 ± 2.9	13.8 ± 3.6	15.6 ± 7.1
Male	18-24	27.5 ± 9.2	33.4 ± 7.5	36.3 ± 11.7
	35-44	33.1 ± 10.6	35.9 ± 6.9	35.5 ± 8.6
	62-74	23.3 ± 5.9	28.8 ± 9.5	25.3 ± 4.3

Table 13. Mean ± one standard deviation of the strength of neck flexor muscles in lbf for males and females, grouped in terms of age and stature (percentile). (From Foust, et al., 1973)

Gender	Age	1-20th Percentile	40-60th Percentile	80-99th Percentile
Female	18-24	24.1 ± 7.5	28.7 ± 6.2	28.7 ± 8.2
	35-44	23.5 ± 6.6	27.7 ± 6.0	28.2 ± 6.3
	62-74	17.9 ± 5.2	23.5 ± 6.3	26.7 ± 10.3
Male	18-24	33.6 ± 4.4	36.6 ± 11.6	43.0 ± 8.5
	35-44	43.5 ± 8.8	46.3 ± 10.5	45.6 ± 10.0
	62-74	32.2 ± 9.1	35.1 ± 10.0	33.5 ± 4.8

Table 14. Mean ± one standard deviation of the strength of neck extensor muscles in lbf for males and females, grouped in terms of age and stature (percentile). (From Foust, et al., 1973)

V.   ELECTROMYOGRAPHY (EMG)

1. Basmajian JV, DeLuca CJ. Muscles alive: their functions revealed by electromyography. 5th ed, Baltimore:Williams and Wilkins, 1985.

This text is the most often cited reference for studies utilizing EMG recordings. The following is a summary of the pertinent information relative to strength studies.

Electrode interface: The detection electrode surfaces should be oriented in a direction perpendicular to that of the muscle fibers. A bipolar electrode configuration is the most selective. Two detection Ag-AgCl electrodes (1 cm apart for surface electrodes) are used to detect two potentials in the muscle tissue of interest, each with respect to a reference electrode, which has been placed on an electrically unrelated tissue. The two signals are then fed into a differential amplifier to eliminate common mode noise. The size of the electrodes should be as large as possible, although the advantages diminish above 5 mm diameter. Amplifier characteristics should include gain up to ±1 V, input impedance $> 10^{12}$ Ω in parallel with 5 pf capacitance, CMRR > 100 dB, low input bias current (< 50 pA), noise $< 5\mu$V RMS and a surface electrode bandwidth (BW) 20 - 500 Hz. The preferred location of an electrode is in a region halfway between the center of the innervation zone and the further tendon.

Signal characteristics: During a sustained contraction, the conduction velocity along the muscle fibers decreases. As a result, the time duration of the MUAPs (muscle unit action potential) increases. This change in shape of the MUAPs is reflected in the PSD (power spectral density function) as a shift towards the lower frequencies. Therefore, more signal energy passes through the tissue between the active fibers and the surface electrodes. Muscle tissue and differential electrodes act as low pass filters (LPF). As the distance between the active fibers and the electrodes increases, the bandwidth of the tissue-filter decreases. The increasing effect on the signal, due to the tissue and electrode filtering, overrides the simultaneously decreasing effect of firing rate. This does not occur with indwelling electrodes and the resulting RMS values may look different.

The firing rates of motor units are muscle dependent. In small muscles, such as those in the hand, the firing rates begin firing at relatively lower values and reach relatively higher values than those in motor units of larger limb muscles. In larger muscles, the firing rates tend to plateau at 20 to 25 pps, whereas in small muscles, the firing rates have a greater dynamic swing, reaching 60 pps. Firing rate should be measured over at least 400 to 1000 ms for meaningful values. Smaller muscles rely primarily on firing rate, larger muscles on recruitment to modulate their force. During force contractions, newly recruited motor units may disfacilitate (decrease the firing rate of) previously activated motor units. This interaction may be explained by invoking the involvement of the stretch reflex and recurrent inhibition. This interaction mechanism enables muscles to increase the smoothness of its force output. In smaller muscles (e.g. hands), most of the motor units are recruited below 50% MVC, whereas in larger muscles in the limb, recruitment persists up to at least 90%, possible 100% MVC (maximal voluntary contraction).

Time Domain Analysis: A variety of techniques have been reported in the literature. These include the following. Full wave rectification (result of AC coupled amplifiers) will retain the signal frequency content. Smoothing of the rectified signal is used to extract amplitude-related information (suppression of high frequency fluctuations, i.e. via a LPF) - the smaller the BW, the greater the smoothing. Averages or means of rectified signals (digital equivalent to smoothing) are typically done using moving averages for a time varying average of a complete record of a signal. The authors suggest using a window of 100 to 200 ms. Integration (area under the curve in V· s or.mV · ms) is most commonly used and abused technique. This can only be applied to the rectified signal. The only difference between integrated rectified value and the average rectified value is that the latter is divided by T (the time over which the average is calculated).

The authors recommend calculating the Root-mean-square value above the other techniques where

$$\text{RMS}\{m(t)\} = (\frac{1}{T}\int_t^{t+T} m^2(t)dt)^{1/2}$$

Frequency Domain Analysis: A Fourier Transform of the EMG signal is often calculated and is primarily a function of the muscle unit action potential waveform and the inter-potential interval. The coefficient of variation (ratio of standard deviation to the mean) is a measure of the regularity with which the motor unit is discharging. The smaller the coefficient, the sharper and higher the peak corresponding to the firing rate in the magnitude of the Fourier Transform. When it is high (0.26, 0.28), then the peak is less sharp and has lower amplitude.

PSD is plotted with linear scales (Y: magnitude (V^2/Hz); X: frequency) , and median frequency, mean frequency are calculated between the 3 dB to 3 dB points of the spectrum. Median and mean are the most reliable terms while the median is less sensitive to noise.

Effects of fatigue: Fatigue can be defined as one of four types:
        Subjective fatigue: decline of alertness, concentration, motivation, other psychological factors
        Objective fatigue: decline in work output
        Physiological fatigue: changes in physiological processes
        Localized muscular fatigue: associated with external manifestations, such as inability to maintain a desired force output, muscular tremor and localized pain. Effects are localized to the muscle of group performing the contractions.

The frequency components of surface EMG decrease (shift to lower components) when a contraction is sustained, along with an increase in amplitude. These have been observed often and in various muscles throughout the body. These two factors are related since with greater lower frequency content, more of the signal is passed through the LPF effect of the body tissue. The magnitude of this phenomenon depends on the force of contraction, time into the contraction, electrode type, subcutaneous tissue thickness and the particular muscle investigated. Spectral shifts are more dramatic near the beginning of a sustained contraction and the amplitude change is more pronounced near the end.

The EMG waveform will be a function of the particular muscle that is contracting and the force level of the contraction. These two variables determine the fiber type, number, firing rate and location of the motor units involved, as well as the state of blood flow. (As force output increases, oxygen demand increases, requiring an increase in blood flow.) However, the intramuscular pressure also increases, eventually leading to occlusion of the arterioles and reduced blood flow. Studies of biceps and other arm muscles showed that blood flow peaked at 25% MVC (maximal voluntary contraction) and reduced to below resting levels above 50% MVC.) During sustained fatiguing exertions, (1) for constant force contractions (number of active motor units essentially fixed), the dominant factor was the amount of acidic by-products that remained in the muscle; and (2) for force varying contractions, the effect of tissue filtering of the newly recruited motor units also played a prominent role.

To measure the fatigue associated frequency shift, the ideal BW is 0 - 500 Hz, however for practical purposes, i.e. AC coupled amplifier, use 20 - 500 Hz. Rather than using the change in amplitude, which is effected by various mechanical electrode interface factors, or measures of total energy content, the authors talk about tracking characteristic frequencies. Namely, the median, mean and mode frequencies. The median frequency divides the power density spectrum into two regions with equal power. The mode frequency is the frequency of the peak of the spectrum. All three are linearly related (in a mathematical sense) to the conduction velocity of the muscle fibers. The mode frequency is the least useful because the EMG is a stochastic signal without a smooth and sharply defined region near the peak value of its spectrum. So they recommend using mean and median frequencies. These may decrease by more than 50% by the end of a sustained isometric contraction, although the actual amount is dependent on which muscle is monitored. Recovery takes 4 to 5 minutes. This is consistent with the time required to remove the built up lactic acid during localized muscle fatigue. Median frequency may be influenced by a decrease in temperature and ischemic conditions in the muscle. Increase in temperature leads to an increase in median frequency.

Information pertaining to various muscle groups:

While the control strategy for activating individual motor units does not alter with training, the interaction of muscles is altered by training. In particular, rhythmic repetitive training movements leads to progressive inhibition of the antagonist during flexion and extension movements until the inhibition is complete (this eliminates wasteful antagonist activity).

Ligaments play a greater role in supporting loads than is generally thought and, in most situations where traction is exerted across a joint, muscles play only a secondary role. Normally ligaments, not muscles, maintain the integrity of joints.

Three parts of the **deltoid** are active in all movements of the arm. In flexion and medial rotation, the anterior part is more active than the posterior; in extension and lateral rotation, the posterior is the more active; and in abduction the middle part is the most active (the authors cited a 1949 study). The principal action of the anterior deltoid is forward flexion of shoulder joint and participation in elevation and slightly in abduction of the arm. The middle portion strongly acts in abduction and arm elevation and has slight participation in flexion and extension. The posterior part has its principal action in extension, with inconsistent or slight action in abduction and arm elevation (the authors cited 1958 and 1969 studies).

The **Biceps brachii** has a slight action in flexion of shoulder joint and nil activity during abduction with the arm medially rotated. During flexion with resistance and with the elbow straight, both heads of the biceps are always active. During abduction with resistance both heads are active and adduction with resistance recruits activity in half of the short heads and nothing in the long head. Pulls (even heavy ones) with the arm hanging straight down are associated with no EMG activity in the deltoid, biceps and long head of the triceps.

The biceps is generally active during flexion of the supine forearm under all conditions and during flexion of the semiprone forearm when a load ($\approx$ 1 kg) is lifted. When the forearm is prone, usually the biceps plays little role in flexion, maintenance of elbow flexion and in antagonistic action during extension even with a load. The maximum strength in the elbow flexors in both isometric and dynamic contractions is smaller with the pronated rather than supinated forearm. The biceps is not a supinator of the extended forearm unless supination is resisted.

The **Brachialis** is a flexor of the supine, semiprone and prone forearm in slow or quick flexion, with or without a load. This is because the line of its pull does not change with the various positions. The brachialis used in maintenance of specific flexed postures of the elbow.

The **Brachioradialis** does not play any appreciable role during maintenance of elbow flexion and during slow flexion and extension without a load. When a weight is lifted during flexion, the brachioradialis is generally moderately active when the forearm is semiprone or prone and slightly active when supine. It is usually active during quick flexion and extensions in all three forearm positions.

All three muscles act maximally when a weight is lifted during flexion of the semiprone forearm. This is the natural position of the forearm and position of greatest mechanical advantage.

The long head of the **triceps** is inactive during active extension of the elbow. The medial head is always active and is the prime extensor of the elbow, though the lateral head shows activity as well. Against resistance, the long and lateral heads are recruited.

The **Semispinalis capitis** has one main function: extension of the head on the neck. It probably also has an antigravity function when one leans forward. The **Splenius capitis** is active during extension as well as during head rotation to its own side. It is probably as important a neck rotator as the **sternomastoid**. The latter shows activity when one raises their head from a couch.

2. Lippold OCJ, Redfearn JWT, Vuco J. "The electromyography of fatigue." Ergonomics, 3:121-32, 1960.

This paper describes changes in electrical activity during and following fatigue. EMG recordings of the calf and small hand muscles using concentric needle electrodes were taken from an unspecified number of males and females of "average physical fitness." It was found that fatigue led to modifications in the electrical activity measured on whole muscles. Sustained exertions increased the rhythmic activity of groups of muscle units within the muscle leading to electrical "bursts" of about 8-12 Hz (i.e. visible tremor). The authors stated that muscle spindles are also reportedly sensitive to local changes, such as ischemia and temperature fluctuations and that their responses may be modified by fatigue.

The authors noted that as voluntary contraction progressed, electrical activity increased. When a constant tension was maintained for several minutes, action potentials became closer together and increased in amplitude. Also, during and immediately after repetitive activity, peak to peak amplitude was reduced while duration of each action potential was lengthened.

The EMG demonstrated two types of synchronization. First, action potentials were grouped at intervals of 60 - 130 ms with the groups and intervals becoming more pronounced as fatigue progressed. After prolonged contractions, slow tremor waves may also develop. Second, during strong contractions and particularly after fatigue, large sinusoidal waves (about 25 - 30 Hz) appeared using needle electrodes. The authors also noted that migration of electrical activity from one muscle to another occurred, serving to spread the exertion to adjacent motor units.

With measurements taken in whole muscles voluntarily contracting at a given tension, the integral with respect to time of the action potentials gradually increased. At a tension between 10 - 80% of maximal, the integral decreased slightly during the first 1 to 2 min then increased until a voluntary end point was reached, between 5 to 10 min later. As fatigue increased, the end point was reached faster and curve was steeper. With an intact circulation, recovery after fatigue was complete in about 1 min. The authors asserted that adequate blood supplies were essential for recovery - if supply vessels were occluded, then the integrated electrical activity remained high even after the exertion was stopped.

To summarize, muscular fatigue induced EMG changes, in that action potentials became smaller in amplitude and longer in duration, large waves (25 - 30 Hz) appeared and synchronous firing of motor units occurred.

3. Lance BM, Chaffin DB. "The effect of prior muscle exertions on simple movements." Human Factors, 13:355-61, 1971.

In this paper, simple discrete arm movements were studied before and after muscle exertion with EMG. After training to familiarize themselves with the apparatus and tasks, six males performed a sustained static exertion of the elbow-flexion muscle group (maintain a 90° elbow angle while supporting a 20 lb weight as long as possible) followed immediately by five no-load movement trials. This was then repeated six times. After a five minute rest, a recovery phase followed consisting of a 10 s 20 lb hold, 25 no-load movement trials and a final EMG recording. To measure elbow flexion, the active EMG electrode was attached directly above the belly of the biceps-brachii muscle, the reference electrode was attached on the medial side of the elbow and the ground electrode was attached to the lateral side of the elbow. Analysis of EMG power spectra was computed from 0 - 200 Hz.

The authors cited previous research which correlated EMG power decreases in the 40 - 70 Hz band during muscle exertions with intermuscular discomfort and loss of psychomotor performance of an eye-hand coordination task. It was found that the preexertion 40 - 70 Hz band comprised 32.5% of the total EMG

power while the postexertion 40 - 70 Hz band compromised 22.5% or less of the total. (They considered a drop from 44 to 26% of total power a minor change and a drop from 38% to 14% a major change.)

No statistically significant change in reaction time or initial adjustment time were found but significantly greater overshoot and stabilizing times were demonstrated for those subjects who had large decrements in EMG power. This was primarily attributed to the loss of their ability to inhibit muscular tremor.

4. Khalil TM. "An electromyographic methodology for the evaluation of industrial design." Human Factors, 15:257-64, 1973.

This paper reported on a proposed technique for evaluating industrial designs based on EMG recordings of the involved muscles. For the purposes of this report, these were the pertinent findings relative to the use of EMG recordings. An increase in muscular effort was accompanied by an increase in action potential produced by muscles as well as the integrated EMG signal. The author proposed using a total integrated muscular activity method which takes individual EMG signals, AC couples them to an amplifier, then takes the absolute value of the signals, and then feeds them into an analog computer for integration.

For static loading and dynamic tests utilizing the arm, Khalil monitored the biceps, triceps, brachioradialis and deltoid muscles. He urged that electrodes should be placed as close as possible to the muscle to be monitored.

VI.   OPERATIONAL CONSIDERATIONS

1. Strength requirements for tactical aircraft based on an interview with NAWC F/A-18 Instructor Pilot CDR M. Messick (6 Jan 95)

        Isometric force exertions are not a problem in fly-by-wire aircraft. Muscular endurance and fatigue is. The latter are important factors in aerial combat maneuvers, which typically includes a sequence of engagements featuring short duration sustained G turns (typically 3 - 4 s; 10 s is a long turn), then the pilot unloads the aircraft, regroups and pulls G's again. By the second turn, it is not unusual for an experienced pilot to use both hands or use their thigh or knee to help push the control stick. During training, pilots fly a series of bombing runs (for example 24 runs in A6) in which the bomb is released at 8,000 ft and then the pilot performs a +4 to 5 Gz climb such that the aircraft does not descend lower than 5,000 ft and then the maneuver is repeated over and over (about once per minute). He suggested that out of control, high angle of attack departures featuring high negative G loads and high pitch, roll and yaw angles, though not high +Gz loads, might demand higher muscular capabilities. He indicated that an out of control condition is not associated with high +Gz, but does have an initial violent jerk, perhaps 135° (yaw 45 to 90°) then the aircraft descends in a falling leaf pattern. Hunter's out of control simulation (Hunter and Weiss, 1953) is inconsistent with modern aircraft capabilities.

        Note that the Tom Cat (F-14) has heavier stick forces than the Hornet (F/A-18). P3 and E2 aircraft have even higher strength requirements. For example, when the hydraulic boosters fail a P3 pilot has the arduous task of using direct cables with which to manipulate the control surfaces.

        An extremely demanding task occurs when an aircraft develops a trim malfunction in which a pilot has to hold cross controls and maintain a yaw free attitude while applying enough rudder to compensate for long periods of time (e.g. 5 to 30 min). This occurs during a single engine failure condition where the pilot must maintain the rudder pedals at a position less than full throw and compensate with the control stick. Neutral trim becomes, for example 8 to 10 lbf instead of 0. Particularly demanding is the case when one has to fly out of trim for awhile then has to land, possibly

under adverse weather conditions. The requirement for precision control after fatigue is extremely physically demanding (the need to null out trim and fly manually).

2. Muscular strength and endurance requirements for various critical tasks performed in USN fixed wing aircraft were assessed based on a survey of aircraft model managers conducted by LCDR T. L. Pokorski (NAMRL) in 1994. Based on the managers' experience, they were asked to specify whether these tasks required muscular strength (isometric) and/or endurance, if they required arm, leg, abdominal or neck muscle group or whole body exertions, the frequency of these critical tasks (once, few or many) and whether such tasks were considered emergency or survival tasks. The following is a synopsis of their responses.

A-6E: The manager cited evasive maneuvering during hostile engagements, low level navigation, low level bombing missions, acrobatics and high altitude bombing as tasks requiring muscular strength and endurance. The manager cited carrier landings, tanking operations and ferry missions as tasks not previously performed by women, although he further stated that muscular strength and endurance were not factors in these environments. This comment was submitted: "... strength requirements for the A-6E mission are similar to those in which female naval aviators and naval flight officers are currently involved. They have completed the same training syllabus and currently are flying with shore-based squadrons that are involved in very similar missions from a strength required standpoint."

EA-6B: The most strenuous task is the "Runaway Stabilizer Trim." This requires a 20 - 30 lbf full stick deflection held for up to 60 min due to flight deck availability. This requires arm muscular strength and endurance during an emergency. To quote from the manager's comments, "When combined with a carrier environment, this situation requires a good deal of muscular endurance. This is especially true when flying the final approach after holding these inputs for a prolonged period of time." Freeing stuck auto throttles requires about 35 to 55 lbf of arm strength. Rudder pedal force requirements may reach as high as 110 lbf while flying in a single engine configuration. This can occur on final approach, with an engine loss after takeoff rotation (where balanced flight is critical), and during practice approaches and under emergency conditions. Isometric arm strength requirements during ejection during a lower ejection handle ejection are 75 lbf (armed configuration) to 120 lbf (safed configuration). During a face curtain handle ejection, force requirements range from 25 to 70 lbf.

AV-8B: To free stiff or jammed flight controls requires isometric arm and/or leg forces greater than 35 lbf; up to 60 lbf or higher with increased aerodynamic loads. A hydraulic failure in System #1 requires rudder forces greater than 35 lbf. The manager commented that the consensus reaction from the various pilots was that was no normal sortie task that would require special consideration based on muscular abilities alone.

F-4B/N: The 5 - 10 lbf required for right hand/arm roll and lateral movements and the 5 lbf necessary for the left hand to move the throttles were described as endurance tasks. 20 -40 lbf isometric exertion by the left arm are often required to produce the breakout force from the "auto throttle." Normal rudder inputs are 10 - 20 lbf, while under emergency procedures (e.g. hardover) reach about 50 - 60 lbf - both isometric and endurance exertions. Applying the toe brakes requires leg inputs of about 10 - 20 lbf. About 80 lbf (arms, back and legs) are required to open the canopy during manual egress with no air pressure for assistance.

F-5E: Performing anti-G straining maneuvers, pulling +6 - 7 Gz and "adversary mission" scenarios require arm, leg, abdominal, neck and whole body exertions. Coping with stick forces while pulling Gs requires arm isometric strength and moving the head under G-load requires neck muscle isometric strength. This task occurs frequently.

F-14A/B: Arm muscular strength and endurance are required while manipulating the stick during hard maneuvering. According to the F-14A NATOPS Manual (NAVAIR 01-F14AAA-1, page IV-11-2) the pilot can be faced with 10 lbf per "G" due to the lack of leverage with the position of the stick (up to 65 lbf at +6.5 Gz). Maneuvering stick force commands a predictable increase in force relative to the G-load (about 4 lbf /G) which varies little with altitude, airspeed, loading or center of gravity position. While the stick forces are not especially high, the stick placement (relatively close to the torso) can provide less leverage to attain a given G-load. This can become more tiring, particularly at lower airspeeds and higher angle of attack, where the load can reach 10 lbf /G. During single engine operation, a constant rudder force must be maintained which can be physically demanding over a period of time. When one engine is out and the other is in military power, it takes about 15 lbf for the F-14A (20 lbf for the F-14 B/D) to neutralize the yaw of the aircraft. With one engine off and the other is in full afterburner, it takes about 20 lbf for the F-14A (25 lbf for the F-14 B/D) to neutralize the yaw of the aircraft. In the event that the boosted throttles are lost, at least 8 lbf per throttle are required as compared to the normal 3 lbf required in the boost mode.

F-14D: Under normal conditions, the manager stated that very little force is required to operate the F-14D. Control stick forces requires about 15 - 20 lbf for forward input and approximately 5 - 10 lbf for aft input. The manager describes this as both an arm muscular exertion and endurance task, which may occur often.

F-18A/B/C/D & TF-18A: Ejection seat pull force involves a two step procedure in which a 15 - 40 pull removes the handle from its housing and a continued pull of 30 - 60 lbf is required to pull both sears from the dual initiators. The manager included additional points which he did not categorize as critical tasks. These were a stick force of 3.5 - 4.5 lbf /G; some aircrew find it "difficult" to lower the hook handle; rudder force inputs during asymmetric situations may be fatiguing for "long periods of time;" stick force above 22° angle of attack (AOA feedback provides increasing stick force of 35 lbf when AOA > 22°) - many pilots use two hands during high AOA maneuvering; and the auto throttle breakout requires 12 lbf per side and during a mechanical failure, each side requires 68 lbf per side.

S-3B: The manager submitted the following isometric and endurance force estimates: emergency flight control system (hydraulic failure) requires 80 lbf over 45 minutes; pitch trim stuck in full up or down position requires 50 lbf over 30 minutes; single engine waveoff/failure after takeoff requires 50 lbf over 5 minutes; inflight refueling/tanking requires 40 lbf over 15 minutes; defensive combat maneuvering requires 40 lbf over 1 minute; a blown tire while still on the runway requires 40 lbf over 2 minutes; anti-submarine warfare requires 10 lbf over several hours; and an emergency egress requires 10 lbf of isometric strength.

TA-4F/J: Controlling the aircraft with a "manual flight control disconnect" (flight controls disconnected with complete hydraulic systems failure) requires arm strength and endurance during this emergency procedure. After the disconnect, the stick forces are "high, " above 300 KIAS, forces are "extremely high." For example, a 20°/s roll rate at 300 KIAS during a disconnect procedure would require a minimum force of 40 lbf to trim the aircraft over a minimum of 5 s.

T2-C: The following tasks are required parts of the training program prior to being "winged." Flying with a run-away trim (nose down) requires 30 - 40 lbf of stick force for the remainder of the flight. This requires arm strength and endurance under emergency and survival conditions. Performing a repeated series of +3.5 - 4 Gz turns ("Gun Pattern") requires arm strength and endurance. A "minimum radius turn" in which a pilot pulls 4 G for 15 - 30 s during the onset of the maneuver, then holds that input for 2 min is part of the familiarization syllabus requires a one time application of arm strength and endurance. "Rolling acrobatics (e.g. loops) during which a 4 G-load is applied for 15 - 30 s requires a few applications of arm and abdomen

muscular strength and endurance. During recovery from "out-of-control" flight (spin) requires 10 - 20 lbf applied to the rudders involves a few applications of leg muscular strength and endurance. Hydraulic boost off landings are simulated during training during which 10 - 20 lbf applied to the stick requires arm muscular strength and endurance during an emergency. The manager gave the following comment, "Compared to "fleet" aircraft, the T-2C is "average" when it comes to control forces. (We) currently have female instructors and students attached to the training squadron. There have been no situations where, due to strength, we've experienced any problems safely completing the maneuvers."

T-44A: During emergency gear extension, a pilot must pump the level with the right hand and the manager estimates that less than 50 lbf for about 3 - 5 min would be required. Pulling back on the elevator force control with the left hand during aircraft rotation during takeoff requires less than 50 lbf (isometric). The manager commented that the T-44A is very light on the controls and is not very demanding to fly. The rudder input is the only really demanding exertion requirement with the "much practiced engine-out work."

T-45: T-45 cockpit canopy closure requires 50 pounds of overhead pull force and a horizontal push down motion (isometric arm strength). Emergency landing gear extension requires a 50 lbf horizontal arm muscular while the fuel shutoff handle extension requires 30 pounds of pull force.

VII.   FEMALE +Gz-TOLERANCE

1. The following is a synopsis of USN female aviator performance during NAWC G-Tolerance Improvement Training (G-TIP) from 1989 to 1994. Aviator physical characteristics are listed in Table 15 and tolerance data is in Table 16.

No.	Age	Height (in)	Weight (lb)	Total Flight Hours	Total Tactical Flight Hours	Aircraft	Flight Status
1	35	60.0	125	4	4	AV-8	Physiologist
2	26	67.5	145	0	0	none	Physiologist
3	41	63.5	117	1000	0	TA-4	Physiologist
4	33	70.0	unk	30	0	unk	Physiologist
5	35	66.0	117	1900	0	T-34	Pilot
6	26	65.0	122	88	5	F/A-18	Physiologist
7	29	68.5	145	200	0	unk	Physiologist
8	30	67.0	140	1200	75	A-6	unk
9	29	69.0	155	400	0	F/A-18	unk
10	25	65.0	135	300	0	A-6	NFO
11	26	62.0	130	2	unk	F/A-18	Back Seat
12	34	71.0	150	2300	2100	F/A-18	Pilot

Table 15. Physical characteristics of female aviators participating in NAWC G-TIP from April 1989 to May 1994. unk: unknown; No: subject number; NFO: non-flying officer.

No.	Run Type	Max G-load	Duration (s)	Anti-G Suit Inflated?	Light Loss	Run Termination
1	GOR	7.7	77	No	60	PS
	ROR	6.0	17	Yes	0	PS
	ROR	8.0	10	Yes	0	CS
2	GOR	5.9	60	No	80	PLL
	ROR	6.0	24	Yes	0	PS
	ROR	8.0	8	Yes	90	PS
3	GOR	5.4	47	No	0	PS
	ROR	6.0	30	Yes	0	EOR
	ROR	8.0	15	Yes	60	EOR
	ROR	9.0	12	Yes	0	PS
4	GOR	6.6	53	No	60	PLL
	ROR	6.0	30	Yes	0	EOR
	ROR	8.0	4	Yes	89	LOC
	ROR	8.0	4	Yes	90	PLL
5	GOR	6.3	53	No	60	PS
	ROR	6.0	30	Yes	0	EOR
	ROR	8.0	4	Yes	90	LOC
	ROR	8.0	5	Yes	60	PS
6	GOR	6.2	49	No	65	PLL
	ROR	5.5	30	Yes	50	EOR
	ROR	6.5	15	Yes	85	EOR
	ROR	7.0	15	Yes	75	EOR
	ROR	7.5	15	Yes	90	EOR
	RORX	5.5	15	Yes	unk	EOR
7	GOR	2.7	16	No	60	PLL
	ROR	4.0	20	Yes	75	PLL
	ROR	4.0	25	Yes	0	FAT
	ROR	4.5	15	Yes	90	EOR
8	GOR	7.0	55	Yes	60	PLL
	ROR	6.5	30	Yes	0	EOR
	ROR	7.0	30	Yes	30	EOR
	ROR	7.5	15	Yes	45	EOR
	ROR	8.0	6	Yes	90	LOC
	ROR	8.0	7	Yes	85	PLL
9	GOR	4.8	34	No	60	PLL
	ROR	6.0	30	Yes	0	EOR
	ROR	7.5	15	Yes	90	PLL
	ROR	6.5	20	Yes	90	EOR
10	GOR	4.5	30	No	30	EOR
	ROR	6.0	30	Yes	60	EOR
	ROR	7.5	15	Yes	60	EOR
	ROR	8.5	6	Yes	75	A-LOC
	RORX	6.0	20	Yes	40	EOR

Table 16. G-Tolerance of female aviators participating in NAWC G-TIP from April 1989 to May 1994.

No.	Run Type	Max G-load	Duration (s)	Anti-G Suit Inflated?	Light Loss	Run Termination
11	GOR	4.4	32	No	75	PLL
	ROR	5.5	30	Yes	0	EOR
	ROR	6.0	30	Yes	30	EOR
	ROR	7.0	15	Yes	60	EOR
	ROR	8.0	15	Yes	75	EOR
	RORX	6.0	20	Yes	90	EOR
12	GOR	5.0	36	No	60	PLL
	ROR	6.5	30	Yes	50	EOR
	ROR	7.0	30	Yes	50	EOR
	ROR	8.0	15	Yes	0	EOR
	ROR	9.0	15	Yes	60	EOR
	RORX	7.0	20	Yes	60	EOR

Table 16 (con'd). G-Tolerance of female aviators participating in NAWC G-TIP from April 1989 to May 1994. No: subject number (same as in Table 15); GOR: gradual onset run (1G/10 s); ROR: rapid onset run (2 s rise to plateau); RORX: ROR in "check six" position; Light Loss measured in degrees where 90° is total peripheral light loss; A-LOC: almost loss of consciousness; CS: computer stop; EOR: end of the run; FAT: fatigue; LOC: G-induced loss of consciousness; PLL: light loss $\geq$ 60°; PS: pilot stop.

VIII. AIRCRAFT EJECTION

1. Air Force Systems Command Handbook 1-3 Human Factors Engineering, 3rd ed, Rev. 1. No. AFSC DH 1-3, DN 3M2 section 4.2.1 "Ejection Controls," 1984.

The following summarizes pertinent points referable to the design and use of aircraft ejection controls:

The ability to reach and the response time for ejection control operation is determined by (1) the acceleration vector imposed prior to movement of the body extremities for control initiation; (2) control location in relation to normal flight position of hand and arm; (3) amount and type of personal protective equipment (PPE) worn and restraint devices used; (4) anthropometric shape of the control and its operations and how it interacts with the PPE worn.

Studies of the movement from the flight controls to ejection controls under 1g and high-G loads show that a relationship exists between (1) arm/hand weight; (2) reach movement distance; and (3) the direction of movement relative to the G vector. With a given arm/hand weight, as G-load and/or reach distance increases so does the amount of energy expended and length of time to reach the control. Reach movement begins from the standard throttle and stick locations. Designers must ensure that the reach movement from the standard position is perpendicular or downstream parallel to the G vector and that control activation is accomplished in a motion perpendicular to the G force. Motion in the +Gx plane is easiest, +Gz next, -Gx third and -Gz fourth. +Gx and +Gz loads are the most commonly experienced in emergency situations. Humans require 1 s of actuation time when operating the control under high G with a movement across the G vector. Operation of controls in direct opposition to the G vector requires additional time. Controls should be designed so that the 5th percentile operator has the grip strength to activate them. In order to effectively operate ejection controls the pilot must be properly supported and restrained under G. Controls should be designed such that one motion accomplishes both pre-ejection and ejection functions.

The mean time to respond, reach and adjust a "D" ring ejection control while wearing summer flight suit are as follows: 0.8 s at 1 g; about 0.82 s at +2 Gx, about 1.02 s at +6 Gx; about 0.83 s at +2 Gz, about 1.5

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s at +5 Gz. Based on the weight of a 95th percentile arm/hand, the reach movement distance to the control and the time required for the reach movement, the energy expended to reach the D ring is 0.3 hp at +5 Gz, 0.1 hp at -4 Gx and 0.25 hp at +6 Gx.

2. NATOPS Flight Manual, A1-F18AC-NFM-000, F/A-18A/B/C/D, 15 Sept 1988 (chapter 5).

The following are criteria for airspeed and altitude for ejection. The optimum airspeed for ejection is less than 250 Knots. With wings level and no sink rate, a pilot can eject at ground level at zero airspeed and from ground level to 70,000 feet at 600 knots maximum. If the aircraft is out of control, a pilot should eject by 10,000 ft AGL. Even if the aircraft is under control, for it is essential to eject no lower than 2,000 ft AGL.

There are minimum ejection altitudes for given sink rate, airspeed, dive angle and bank angle. Minimum altitude for safe ejection (F/A-18B) based on sink rate (from Fig. 5-12, p. 5-65) are:

Given 2 s for pilot reaction time, 130 - 150 Knots, straight and level attitude:

fpm	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000
altitude (ft)	50	95	140	190	235	295	380	465	550	625

Given 0 s for pilot reaction time, 130 - 150 Knots, straight and level attitude:

fpm	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000
altitude (ft)	15	30	40	55	70	90	140	195	250	300

The following steps are required to prepare for ejection:
    1. Trade airspeed for altitude (zoom)
    2. Level wings and minimize rate of descent
    3. IFF - Squawk EMERGENCY
    4. Follow radio distress procedures
    5. Stow loose equipment
    6. Cabin Pressure Switch - RAW/DUMP
    7. Shoulder harness lock level - LOCKED
    8. Lap belt and shoulder harness tight, visor down, helmet secured, oxygen mask tight
    9. Altimeter - CHECK (10,000 ft AGL if out-of-control, 2,000 ft AGL if controlled)
    10. Slow aircraft as much as possible

Then a pilot must assume the proper body positioning:
    1. Press head firmly against headrest
    2. Elevate chin slightly (10°)
    3. Press shoulders and back firmly against the seat
    4. Hold elbows and arms firmly towards sides
    5. Press buttocks firmly against the seat back
    6. Place thighs flat against the seat
    7. Press outside of thigh against side of the seat
    8. Place heels firmly on deck, toes on rudder pedals

To initiate an ejection, the following grips can be employed:
TWO-HAND GRIP:
        Grip the ejection handle with the thumb and at least two fingers of each hand, palms towards body. Elbows are kept close to body.

SINGLE-HAND GRIP

Grip handle with the strong hand, palms towards body. Grip wrist of strong hand with the other hand, palm toward body. Elbows are kept close to body.

Then, regardless of the grip used, pull the handle sharply up and toward abdomen, keeping the elbows in, ensuring that the handle is pulled to the end of its travel. A pilot continues to hold the handle until seat/man separation.

Note: In low altitude situations, a one-handle method, using one hand to initiate ejection and the other to maintain the aircraft in a safe operating envelop of the ejection seat, may be required. If firing the seat by this method, particular attention must be paid to maintaining proper body positioning.

The forces required to operate the center control stick are specified in Chapter 4 "Flight characteristics." In maneuvering flight, there is a light but constant stick force per G (3.5 to 4.5 lb/G). Maneuvering stick forces do not vary significantly over the entire operating envelope so long as the angle of attack (AOA) is less than the feedback 22° AOA. During a dive or steep zoom climb, a small but constant forward stick force is required to maintain constant attitude. The flight control system incorporates feedback above 22° AOA. To increase AOA above 22° AOA, aft stick must be applied. The maximum steady state AOA with full aft stick (35 lb stick force) is 45° to 50°. Where feedback AOA is active, maneuvering stick forces are increased significantly.

3. Abati DW, Belcher MF. "An investigation of spinal injury potential from the use of the ACES II ejection seat by lower weight female pilots." Master's thesis from Air Force Institute of Technology at Wright Patterson AFB School of Engineering, Sept 1984. (DTIC #AD-A148 449)

They authors used computer models to assess the potential spinal injury risk of 5th percentile females during ejection with an ACES II seat. Using a computer model, they determined DRI ratings (Dynamic Response Index) and found that, given the limitations in the data set and model assumptions, that 103 lb females were at or within acceptable risk limits of 5% probability. As weight decreases, risk increases. At a grain temperature of 70° F, maximum DRI was 18 ± 1 while at 165° F, DRI was 22 ± 1 (for a CKU-5/A cartridge catapult). The authors caution that this risk assessment may be unrealistic since it was based on using the time-thrust curve for a DKU-5/A cartridge catapult, representing the thrust experienced by a 215 lb individual, as an input into their computer model.

In this report, they included the results of a 1984 USAF female anthropometry survey which are summarized in Table 17.

Age (yrs)	Percentage	Weight (lb)	Percentage	Height (in)	Percentage	Sitting Ht (in)	Percentage
21 - 23	24.2	103 - 110	5.7	62 - 63	1.4	30 - 33	0.9
24 - 26	48.8	> 110 - 120	13.5	> 63 - 66	51.6	> 33 - 36	83.1
27 - 29	14.9	> 120 - 130	29.3	> 66 - 69	38.6	> 36 - 39	16.0
30 - 35	12.1	> 130 - 140	27.3	> 69 - 73	8.4		
		> 140 - 150	11.6				
		> 150 - 160	7.9				
		> 160 - 198	4.7				

Table 17. 1984 USAF female anthropometry survey results. Percentage refers to survey population, not population in general. (From Abati, et al., 1984)

4. Gragg CD, Evans CB, Gilliam WL. "Ejection seat testing for females." Technical report from the 6585th Test Group, Holloman AFB, NM, 1 Nov 1982. (DTIC #AD-A122 870)

A survey from Air Training Command of females flying T-37 and T-38 aircraft in 1982 provided the following basic anthropometric information (Table 18):

Height		Weight		Sitting Height	
Percentile	(in)	Percentile	(lb)	Percentile	(in)
5	64.0	5	114.5	5	33.6
10	64.0	10	116.9	10	34.0
15	64.1	15	120.4	15	34.0
20	64.5	20	122.8	20	34.0
25	64.9	25	123.3	25	.34.5
50	66.0	50	130.0	50	34.9
75	67.5	75	141.0	75	35.8
90	69.0	90	149.5	90	36.8
95	70.0	95	155.0	95	37.1
Mean ± 1 SD	66.2 ± 1.9	Mean ± 1 SD	131.8 ± 12.2	Mean ± 1 SD	35.0 ± 1.1
Range	63 - 72	Range	102 - 166	Range	33.0 - 37.5
Number	109	Number	109	Number	40

Table 18. Physical characteristics of female aviators in 1982. Percentile is based on this sample population. (From Gragg, et al., 1982)

5. Hunter HN, Weiss HS. "Pilot's ability to simulate an emergency escape with various types of ejection seats while subjected to a fluctuating acceleration." Aviation Medical Laboratory Letter Report TED ADC AE 6303, 3 Nov. 1953.

To simulate uncontrolled flight, the authors used a fluctuating G pattern in which positive G varied from 1.5 to 6.5 G at 8 G/s while the subject pitched and/or rolled through a maximum angle of 36°. Before each run, the pilot performed a satisfactory 1 g ejection sequence for each of three different ejection seats. The subjects wore full flight gear: anti-G suit, inner liner suit, exposure suit, Mae West, parachute harness, attached emergency kit, inner-liner helmet and/or matching crash helmet, oxygen mask, gloves and boots. Subjects were filmed and timed. Study identified problems with each seat and made recommendations. Biggest problem the subjects had was putting their feet into the stirrups under G.

6. Hunter HN, Weiss HS. "Pilot's ability to actuate F9F-6 ejection seat controls under fluctuating G conditions." Aviation Medical Laboratory Letter Report TED ADC AE 6303.1, 16 Sept. 1954.

This report was similar to Hunter, et al. (1953) except for seat used and that they also tested subjects in minimal flight clothing consisting of anti-G suit, parachute harness, helmet and gloves. The acceleration pattern fluctuated positive G from 1.5 to 7 at 8 G/s while the subject pitched and/or rolled through a maximum angle of 72°. The maximum acceleration rate of change of roll was 5.8 radians/sec^2 and maximum acceleration rate of change of pitch was 4.5 radians/sec^2. Subjects performed the ejection sequence at 1 g to simulate the time required to eject during straight and level flight. Each subject had four series of runs. First was 5 s under the G pattern to familiarize the subject. Second run lasted 20 s during which the pilot wearing full flight gear) was told to eject without being instructed in the proper procedures. Third run repeated the second run after the pilot was instructed in the proper manner to actuate the face curtain. The fourth run also lasted 20 s with the pilot in minimal flight gear. The longest time recorded was during the third run.

7. Hill JH, Brown JL, Peck LH. "Pilot's ability to actuate cockpit controls under G conditions." Aviation Medical Laboratory Letter Report TED ADC AE 6303.1, 1 Apr. 1957.

This reports on a similar study to Hunter et al. (1954) with these differences: this study looked at a summer flight suit versus pressure suit. Subjects were seated with their feet on the rudder pedals, right hand on the control stick, left on the throttle at the full position. The test procedure required that the subject (1) pull the throttle all the way back, (2) slip his feet from pedals to the floor, (3) release the stick and (4) grasp face curtain handles with both hands and pull curtain out to its full extent. With a plateau G load of 5 G, the subjects were exposed to a low fluctuating G series (1 to 4 G at 3 G/s), or a high fluctuating G series (1.25 to 6.5 at 5.5 G/s) while pitching and rolling as in Hunter et al.(1954). Subjects were signaled with a light to begin the sequence 4 s into the run and given an additional 20 s to complete the task or the centrifuge would automatically stop. 3, 4 and 5 G ROR (5 s onset) to plateau were also run with the signal to eject given at peak G and subjects given the same 20 s to complete the task.

8. Hill JH, Webb MG "Pilot's ability to actuate ejection controls; final report concerning." Aviation Medical Laboratory Letter Report TED ADC AE 5205, 5 Feb. 1959.

This reports on the ability of subjects to access a "D" ring and face curtain while wearing a summer flight suit or full pressure suits (with or without inflation) and while sitting in two different ejection seats (McDonnell-Stanley and Martin-Baker). Subjects were exposed to G profiles with 5 s onsets, 10 s at plateau and 8 s offset times. G vectors included +1 to +6 Gz, +1 to +6 Gx, -1 to -5 Gx and -1 to -4 Gy. Runs stopped before 10 s at plateau with successfully initiated ejection. Subjects received a signal to begin the ejection sequence (a light was illuminated) within 3 s of reaching plateau. Reaction time from the point at which the light was illuminated and maximum G-load attained for successful ejection were measured. The forces required to actuate the ejection controls in the McDonnell-Stanley seat were 15 lbf to detent and 20 lbf to fire face curtain and 28 lbf to detent and 35 lbf to fire the "D" ring. To initiate an ejection sequence in the Martin-Baker seat required 26 lbf to detent and 24 lbf to fire the face curtain and the forces to actuate the "D" ring were not reported.

The authors found that subjects had the most difficulty activating the "D" ring while exposed to -Gx and -Gy loads. Little difference was found in their ability to actuate the controls when measurements taken during +Gz were compared to those taken under +Gx stresses. Proper restraint was critical for success - improper restraint was the primary cause for failure. Inflating the pressure suits under G-loads sometimes hindered and sometimes helped the subjects, i.e. what could not be reached at 1G with full pressure could under 3 of 4 vectors.

IX.   PERFORMANCE

1. Angel SM, Marley RJ Stadtlander L. "Perceived exertion scales: toward development of improved verbal anchors." Proc. Human Factors & Ergonomics Soc 38th Annual Meeting, 1994; pp 626-30.

Based on observations made by primarily college students of video tapes of five actual work segments the following alternative verbal anchors to Borg scale (Borg GAV (1982) "Psychophysical bases of perceived exertion." Medicine and Sci. in Sports and Exercise, 14: 377-81) were proposed (see Table 19). This scale was not meant to challenge Borg's numeric heart-rate based scale. The descriptors chosen were intended to unambiguously refer to the work itself. For example, Borg's use of the word weak and strong are generally applied to the worker rather than the work itself. Angel indicates that Borg's list tends to emphasize the extremes, with the use of light to heavy qualifiers as predominantly end values, leaving the intermediate range somewhat vague. The advantage of the Angel scale lies in its larger range of intermediate value words, given that most actual work exertion lies in the middle range.

Angel, et al scale				Corresponding Borg scale
Low Effort	Medium Effort	High Effort		
easy				nothing
light				noticeable
	mild			light
	moderate			weak
	somewhat			moderate
	medium exertion			somewhat
	considerable			strong
		strenuous		hard
		difficult		heavy
		heavy		maximal

Table 19. Perceived exertion scales (From Angel, et al, 1994).

2. Lyons TJ. "Women in the fast jet cockpit - Aeromedical considerations." Aviat. Space and Environ. Med. 1992; 63:809-18.

Historically women have demonstrated the capacity to be successful aviators. A review of the scientific literature between 1966 to 1991 pertinent to the role of women in military aviation revealed only minor differences of questionable operational significance between men and women. Women may be more susceptible to motion sickness, radiation and decompression sickness than men, but may be more resistant to cold immersion and altitude sickness. Although men are on the average larger, stronger and more aerobically fit than women, there are large variations within each sex and a large overlap between the sexes. Gender differences in work performance, G-tolerance, heat stress and injury rate disappear when allowance is made for size, strength and fitness. Aeromedical selection criteria can, thus, address individual characteristics without reference to gender. The possibility of fetal damage in early stages of pregnancy (before diagnosis) appears to be perhaps the biggest single medical concern in allowing women access to all aviation and space careers.

X.   BIBLIOGRAPHIES OF STUDIES COMPILING MALE-FEMALE DIFFERENCES

1. Johnson DM. "Navy job-related male-female differences: Annotated bibliography." Technical Report No. NPRDC SR 82-23, San Diego:Navy Personnel Research and Development Center, April 1982. (DTIC #AD-A114 388)

This report represents a literature search of material published between 1962 to 1982. It includes gender based comparisons of various physical and cognitive abilities. The only consistent differences that are pertinent to this discussion are in terms of anthropometrics, weight and strength. While males are consistently larger than females on most anthropometric measurements, the extent and shape of these differences varies greatly. The most important finding was that current (as of 1982) equipment may not permit a large enough range of position adjustment to accommodate a large proportion of females. Johnson reported that females were more susceptible than males to lower back pain and back injury as well as wrist and arm injury, tendonitis, ganglion injury and trauma from repetitive motions. It was also found that weight training is an effective method to increase strength in females and males.

Johnson also provides the following physiological differences which may impact performance in the cockpit. No significant correlation was found between fitness and anthropometric measurements of females but a significant negative correlation was found between fitness and height and weight of males. Females cadets at the USAF Academy were well above civilian counterparts in physical fitness. Males sweat more and start sweating at lower skin and core temperatures than females. Both sexes profit from

heat tolerance training. Aerobic capacity decreases faster and to a greater extent in males than females. However, female aerobic power averages 70 to 75% of males. The increase in pulmonary ventilation while performing maximal and submaximal work at high altitudes was lower for females as compared to males. Male systolic blood pressure rose higher than females under psychological stress. Table 20 presents male/female differences in cerebral hemispheric activity as listed by Johnson.

Males	Females
Hemispheric specialization	Hemispheric equality
Visual-Spatial functioning	Visual-Verbal functioning
Verbal & temporal structuring of auditory information	Verbal & temporal structuring of visual information
Non-verbal & spatial structuring of visual information	Non-verbal & spatial structuring of auditory information
Handedness & sight dominance correlated	Handedness & sight dominance not correlated
EEG amplitudes higher for auditory stimuli to the right hemisphere	EEG amplitudes higher for auditory stimuli to the left hemisphere
Temporal lobe EEG different for right and left hemisphere tasks	Temporal lobe EEG not different for right and left hemisphere tasks
Right hemisphere specialization of perceptual synthesis processing	Disynchrony of hemisphere in perceptual analysis and vocabulary processing
Faster yes-no decisions from left hemisphere stimulation	Faster yes-no decisions from right hemisphere stimulation
Better recall of visual stimuli by mental visualizations of stimuli	Better recall of visual stimuli by mental repetitions of stimuli
Left-handers higher than right-handers on spatial visualization	Left-handers lower than right-handers on spatial visualization
Eye acuity not correlated with sighting dominance	Eye acuity correlated with sighting dominance
Right-handers have larger right than left feet	Right-handers have larger left than right feet

Table 20. Male/female differences in cerebral hemispheric activity (adapted from Johnson, 1982).

Additional bibliographies of reports (with their abstracts) investigating gender related differences of interest in Naval aviation are as follows:

2. Luzier AR, Erickson DG, McKay JR, Baisden AG, Pokorski TL. "Occupational strength testing related to gender-neutral issues in Naval aviation: A selected bibliography." NAMRL Monograph 47, Pensacola, FL:Naval Aerospace Medical Research Laboratory, 1995.

This bibliography presents the results of a literature review to provide background information for the study "Performance-based occupational strength testing for candidate Navy pilots/Naval flight officers." The purpose of this work is to develop an occupational strength battery to establish gender-neutral standards in Naval aviation selection. This research, partially funded by the Defense Women's Health Research Program, was prompted by a congressional decision to allow smaller statured individuals entry into military aviation. The long-range objective of this project is to test and identify individuals capable of meeting specific strength requirements to safely operate Naval aircraft. The cited publications cover the time period from 1972 through October 1994. The literature search was conducted using the following databases: Defense Technical Information Center (DTIC), Medline and PsychLit. The abstracts included in this bibliography are in original form. An index organized by subject matter is provided.

3. Canine MK, Derion T, Heaney JH, Pozos R. "An annotated bibliography of heat tolerance: Regarding gender differences." San Diego:Naval Health Research Center, 1994 (DTIC #AD-A280 755).

The purpose of this technical report is to provide an overview of the literature on the similarities and differences between men and women in their physiological responses to heat stress. Studies that compare thermoregulation in physically fit and sedentary females, as well as research examining the effect of the menstrual cycle on thermal physiology, are included. For each review, a brief synopsis of the methodology and a summary of relevant results are provided. It was the intent of this report to provide a literature resource, not a review paper, regarding gender differences in thermoregulation during heat exposure.

4. Hudgens GA, Torsani-Fatkin LL. "Human performance: Psychological and physiological sex differences (A selected bibliography)." Aberdeen Proving Ground, MD:Human Engineering Lab, 1980 (DTIC #AD-A085 824).

The bibliography is a compilation of 1,571 references dealing with, or related to, the effects of sex differences on human performance. The material is organized into four categories: An overview of sex differences, physiological sex differences, sex differences in cognitive and motor abilities and sex differences in personality. The time period covered is roughly from the 1930's into 1979. An index of first authors is included.

5. Torsani-Fatkin LL, Hudgens GA. "Human performance: More psychological and physiological sex differences (A selected bibliography)." Aberdeen Proving Ground, MD:Human Engineering Lab, 1982 (DTIC #AD-A147 522).

The bibliography, a supplement of Hudgens GA, Torsani-Fatkin LL (1980), is a compilation of 1,891 references dealing with, or related to, the effects of sex differences on human performance. Four categories are defined: an overview of sex differences, physiological sex differences, sex differences in cognitive and motor abilities and sex differences in personality. While emphasis is on literature published in the period 1979-1981, many earlier works omitted from the 1980 bibliography are included. An index of first authors is provided.

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2. Angel SM, Marley RJ Stadtlander L. "Perceived exertion scales: toward development of improved verbal anchors." Proc. Human Factors & Ergonomics Soc 38th Annual Meeting, pp 626-30, 1994.

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